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INTRODUCTION

Several recent procedures for prescribing the gain and maximum acoustic output (MPO) of hearing aids are based on measurements of a listener's dynamic range in specific frequency regions (Byrne and Tonisson, 1976; Berger, Hagberg, and Rane, 1977; Pascoe, 1978). One goal of these procedures is to amplify the average speech spectrum to the preferred listening levels or most comfortable listening levels (MCL) within each listener's dynamic range. Another goal is to limit the maximum output (MPO) of the hearing aid so that amplified speech and other sounds do not exceed the listener's uncomfortable listening level (UCL).

In listeners with normal hearing sensitivity, the most comfortable levels for sound cover a range of approximately 30dB, including the audible area in which the average long-term RMS level of speech is contained. Normal conversational speech, therefore, is at a level normal-hearing listeners would include in their MCL range. In the presence of a mild-to-moderate, sensorineural hearing impairment, the dynamic range of a listener will be smaller because the thresholds are elevated and the UCL is usually at a normal level (Pascoe, 1980; Skinner, 1980). Since the long-term speech spectrum or level of normal conversation does not follow the shift in dynamic range, the hearing-impaired listener now receives speech closer to, at, or even below threshold. Thus, the need for amplification arises.

The prescriptive procedures provide a means for estimating the real-ear gain needed to compensate for the shift in dynamic range, and MCL in particular, from normal. However, no allowance is made for loudness summation for broad-band stimuli, such as speech. The assumption is that the frequency-response of the hearing aid is specified appropriately, and the volume control (with a total range of about 30dB) can be used to set the overall level at the most comfortable listening level. Thus, the presence or absence of loudness summation can be compensated for by changing the volume control. If loudness summation is present at UCL, however, then the estimates of MPO based on frequency-specific stimuli for UCL will be too high, Hearing aids set in this manner will allow loud broad-band sounds to exceed the listener's UCL. This is a more serious problem since listeners do not have control over the MPO of their hearing aids.

Since an understanding of the phenomenon of loudness summation is important for setting the overall gain and MPO of hearing aids optimally, the purpose of this study was to provide some normative data on the relation between the perceived loudness of third-octave bands of noise and that of broad-band noise. In the classic studies on loudness summation, it has been shown that a normal-hearing listener will perceive an increase in loudness when sounds of approximately equal sound pressure levels in two or more critical bands occur simultaneously (e.g., if 60dB SPL tones of 1000 and 4000 Hertz are presented simultaneously, a listener with normal hearing should now preceive a 3dB increase, or a 63dB SPL tone, even though the overall sound pressure level of the two tones remains the same. Zwicker, 1957). If this phenomena should occur for a listener receiving amplification of speech signals, which contain acoustic energy between 250 and 8000 Hertz, it is possible that the levels of gain set for each specific frequency individually will now be providing more overall gain than the listener finds comfortable. This will occur if the person summates the loudness in the critical bands of the speech stimuli.

An important observation from the previous studies on loudness summation is that the greatest summation of loudness occurs within the human auditory system in the region of the MCL for normal-hearing listeners. (Zwicker, Flottorp and Stevens, 1957). Less summation occurs at high sound pressure levels near UCL than in the region of MCL, and there is little or no summation at threshold for normal-hearing listeners (Zwicker, Flottorp and Stevens, 1957). The stimuli used in these studies were pure-tones, tonal complexes or narrow bands of noise between approximately 1000 and 4000 Hertz. Some of these same stimuli were used to test listeners with sensorineural hearing loss.. For those with mild or moderate hearing losses, some showed summation of loudness and others did not; the presence or absence of loudness summation could not be predicted from their pure-tone audiogram (deBoer and Bouwmeister, 1974; Bonding et al, 1978; Martin, 1974; Bonding, 1979; Scharf and Hellman, 1966). These results are not directly applicable to the broadband output of hearing aids. The present study was designed to evaluate loudness summation using broad-band noise between 250 and 6300 Hertz that was shaped according to the threshold, MCL and UCL contours derived from judgments of the loudness of third-octave noise bands. It was hoped that this information would be more clearly and closely applicable to sound amplified by hearing aids. The listeners chosen for this study were normally-hearing. This is a control study for a parallel study that was done with listeners with sensorineural hearing impairments (Matsumoto, 1983).

PROCEDURE

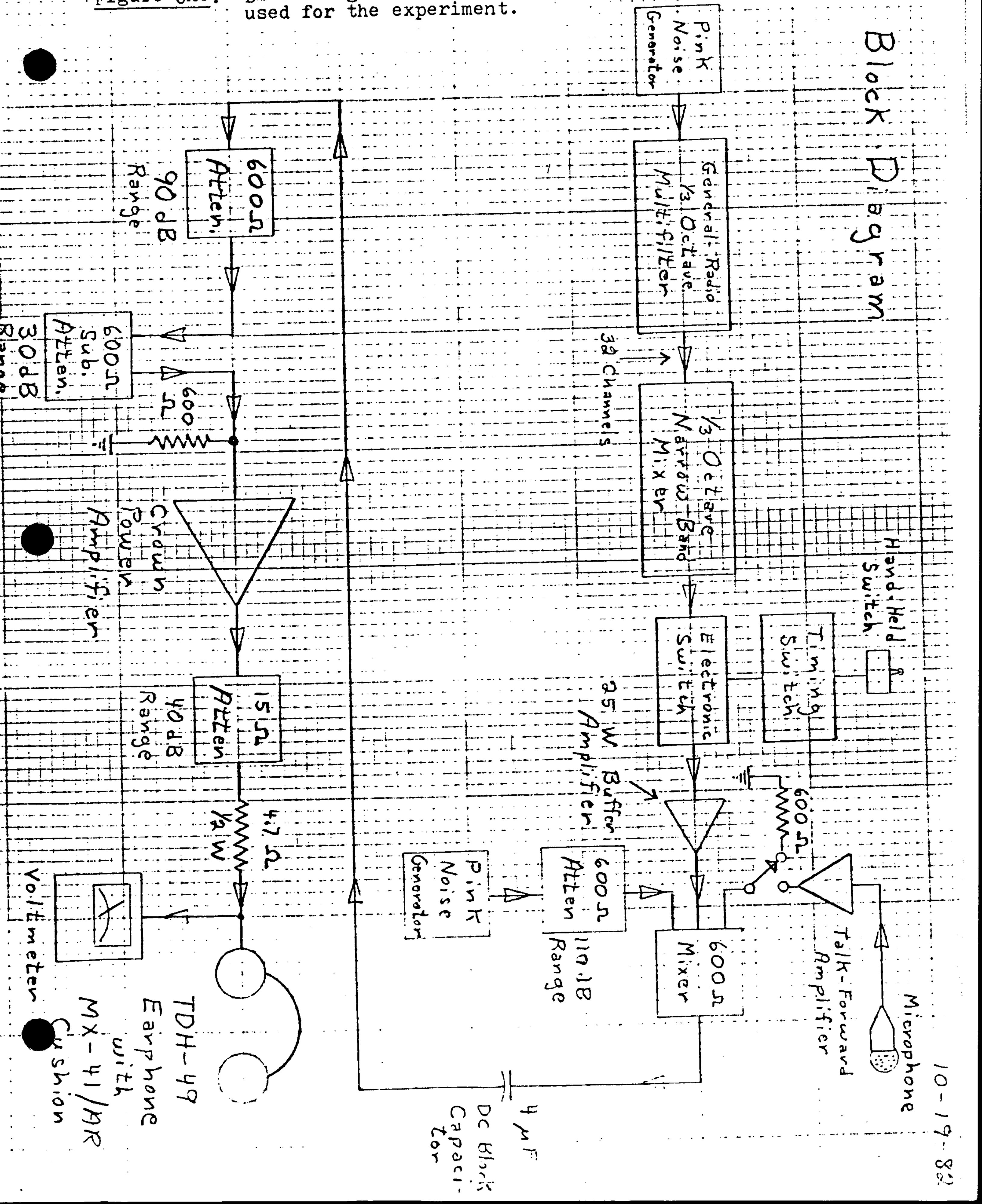
Listeners   Six normal hearing listeners participated in the study. All six listeners were between the ages of 23 and 30 years, female, and all were graduate students in Speech and Hearing Sciences. Each listener was tested prior to the study using a Bekesy sweep-frequency tracing (with a TDH-39 earphone in a MX/41 AR cushion) to insure that they had normal hearing thresholds (see Table one). Thresholds within the range of 10 to 15 dB HTL were considered acceptable for the study. None of the six listeners reported any history of ear disease or any history of familial hearing loss. To avoid confusion, each listener was instructed to use the right ear as the test ear.

Table One: Hearing Threshold Levels (ISO 1964) for each listener in the study derived from a Bekesy sweep-frequency tracing. Thresholds are all of the right (test) ear.

Frequency	250	500	1000	2000	3000	4000	6000	8000 Hertz
Listener 1	0	0	-5	-5	-5	5	-5	10
2	0	5	-5	-5	-5	0	-5	5
3	-5	-5	5	-5	5	10	0	10
4	-5	0	-10	-5	-5	-5	0	5
5	-10	-5	-10	-10	0	-5	0	-5
6	0	5	-10	-10	-5	-10	10	10

Equipment   The equipment used for the study is shown in the block diagram in Figure 1. The equipment consisted of a pink noise generator, a multifilter (General Radio, Model 1926) and mixer, two amplifiers (built at CID), a timing switch (built at CID), a series of three attenuators (Tech Labs), a voltmeter

Figure One: Block diagram of equipment set-up used for the experiment.



(Hewlett-packard), and a TDH-49 earphone in a MX/41-AR cushion.

The mixer enabled us to present single third-octave bands of noise or to sum all the third-octave bands between 250 and 6300 Hertz and present them to the listener. The channel gain in each third-octave band of the multifilter was adjusted to shape the broad-band noise according to each listener's threshold, MCL, and UCL contour.

The timing switch allowed the experimenter to change the noise stimulus from steady to pulsed presentation. Continuous bands of were used only for equipment calibration. For data collection we used a pulsed-noise with a 250 millisecond on-time, which includes a 10 millisecond rise/fall time, and a 750 millisecond off-time.

Two attenuators (total range of 130 dB SPL; each with a two decibel step-size) were included to allow the experimenter to adjust the overall sound pressure level of the stimulus so that the listener could bracket the judgment within a 30 dB range by using a third attenuator (one decibel steps) located in the test booth. The experimenter was able to provide more or less attenuation if the listener was unable to bracket a judgment within the 30 dB range of her attenuator by simply adjusting one of the two control attenuators.

Using the voltmeter and a continuous noise stimulus, the controller was able to calibrate the electrical output to the listener's earphone before each test session. Acoustic calibration was done at the beginning of the study and again upon it's completion. Acoustic calibration was done according to the following procedure. First, the TDH-49 earphone was placed on a NBS-9A coupler with a one inch condenser microphone attached. Then a Bruel and Kjaer audiofrequency spectrometer was connected to the system and set to read on the RMS, slow scale. To calibrate the third-octave bands of noise, the multifilter channel gain was set so that the output was at 115 dB SPL in all third-octave bands between 250 and 6300 Hertz, as measured by the audiofrequency spectrometer linearly. Calibration was considered to be acceptable if the measured sound pressure levels of the third-octave bands were within ±0.5 dB.

The audiofrequency spectrometer was also used to measure the sound pressure in each individual third-octave band of the broad-band noise. For this the one-third octave band filters on the spectrometer were used on the RMS, slow scale. This procedure was done for each broad-band noise shaping (threshold, MCL, and UCL) for each listener. An overall sound pressure level measurement was also taken using the broad-band shaped contours and the linear setting.

Test procedure The study required three days of testing per listener for actual data collection. Data from the first day of testing was considered practice data and was not figured into final experimental results. Day two and Day three were considered actual test days and data collected on these two days was analyzed.

Before starting the experiment, the listeners were given a set of instructions which they read describing the criteria they should use in making their judgments. These instructions were also read by each listener before each test session on each day. (See appendix A for a copy of the test instructions)

Each test day was divided into two sections. For the first section of testing, the listener made judgments of threshold, MCL, and UCL for individual third-octave bands of noise. Two sets of judgments were obtained for the dynamic range with a break provided between each set. To counterbalance learning and fatigue effects, the order of presentation was changed during each test session (Table two). The first set of judgments used an order consisting of threshold, MCL and UCL. After a listener break, the second set of judgments consisted of MCL, threshold, and UCL. The judgments for UCL were always last as it is the most stressful on the auditory system and could have possibly caused a change in hearing sensitivity in the listeners judgments that followed it. For this reason, the listener was always provided with a break after making UCL judgments.

Eight seperate one-third octave bands of noise (250, 500, 1000, 1600, 2000, 3150, 4000, and 6300 Hertz) were used for each set of judgments (threshold, MCL, and UCL). These eight frequencies were presented in a different order for each set of judgments, and the order of these frequencies was selected in a random manner. This procedure reduced the possibility of stimulus-frequency effects.

For each test block, the experimenter informed the listener of which set of judgments to concentrate on (e.g., threshold, MCL or UCL). After the listener re-acquianted themself with the set of

Table 2. A sample of the order of presentation for one test day for the one-third octave bands of noise. Judgments for threshold, MCL and UCL were made for eight individual frequencies. The order of the judgments and frequencies was randomized each time to avoid learning and fatigue effects. Two sets of judgments were made for each day.

JUDGMENT	ORDER OF FREQUENCIES
Threshold	500, 1600, 3150, 6300, 250, 2000, 1000, 4000.
MCL	3150, 2000, 1600, 250, 4000, 500, 1000, 6300.
UCL	4000, 6300, 2000, 500, 1000, 3150, 250, 1600.
----------Listener break----------	
MCL	1000, 500, 6300, 3150, 250, 1600, 2000, 4000.
Threshold	250, 2000, 1000, 4000, 3150, 500, 6300, 1600.
UCL	3150, 500, 2000, 6300, 4000, 250, 1600, 1000.

instructions for that particular judgment, the controller adjusted the two control attenuators to a certain amount of attenuation and presented the test stimulus. The setting on each of the two attenuators, which were labeled attenuator A and B (A=60 ohms, B=15 ohms), were recorded on the data collection sheet for that specific listener. Upon receiving the test signal, the listener adjusted the attenuator accordingly until the desired level was reached. The listener then told the experimenter the dial setting of the attenuator using the talk-back system. The controller recorded this setting on the data collection sheet with the settings of attenuators A and B and labeled this number "listener attenuation". All three attenuator settings were combined to find a "total attenuation" number, which was then subtracted from 115dB SPL, which represented the maximum sound pressure level the equipment can produce with all three attenuators set on OdB attenuation. The final number (115dB SPL-total attenuation(attenuator A+B+listener attenuation)) equals the sound pressure level that each listener perceived to be their individual judgment of either threshold, MCL or UCL for each particular one-third octave band of noise presented.

This procedure was followed until two sets of judgments were completed for threshold, MCL and UCL. When all six sets of judgments were recorded, the experimenter calculated the mean value for each frequency for the two judgments at threshold, MCL and UCL. These mean values, representing the listener's dynamic range for narrow-bands of noise, were then used to set the multifilter to shape a broad-band noise setting between 250 and

6300 Hertz. For each contour (threshold, MCL and UCL), the mean values for the eight frequencies were used and the level for the remaining seven frequencies were calculated by interpolation. (see Table 3). Once a value was assigned to each of the fifteen frequencies, a constant was subtracted from the entire set of numbers so that each individual contour could be transferred to the multifilter. These values were then added to the multifilter calibration for the uniform response, and the final set of numbers was entered into the multifilter and recorded by the experimenter. The multifilter settings for each shaping (threshold, MCL and UCL) were plotted on a clear plastic sheet so that the settings could be changed quickly for testing and for subsequent calibration.

After the multifilter shapings were completed, each listener was required to make another section of judgments this time using the broad-band noise stimulus shaped according to the threshold, MCL and UCL contours. The experimenter set the attenuation in the same manner as for the individual narrow-bands of noise, and the listener adjusted each shaping of the broad-band noise to her threshold, MCL and UCL. The order of the shaping (threshold, MCL or UCL) was randomized, and for each shaping either the threshold or MCL judgment was made first. The UCL judgment was always made last to avoid auditory stress and fatigue. Once judgments of threshold, MCL and UCL had been made for all three shapings of the broad-band noise, a second set of judgments were made with another randomization of stimulus and judgment order.

Table 3. A sample of the interpolation procedure used to transfer the mean judgments from the listener's dynamic range to the multifilter in the shape of each listener's threshold, MCL and UCL contour. These shapings were then used to present the broad-band stimulus to each listener for another set of threshold, MCL and UCL judgments.

Threshold		Listener 1		
Frequency	mean judgment	normalization	multifilter constant	multifilter shaping
250	27	+14	+1	+15
315	20	+7	+1	+8
400	13	0	0	0
500	6	-7	0	-7
630	6	-7	0	-7
800	6	-7	-1	-8
1000	6	-7	-2	-9
1250	6	-7	-1	-8
1600	6	-7	-1	-8
2000	8	-5	-2	-7
2500	6	-7	-2	-9
3150	3	-10	-3	-13
4000	9	-4	-2	-6
5000	13	0	-4	-4
6300	18	+5	+1	+6

Column one represents the fifteen frequencies used to shape the broad-band noise; column two represents the mean of the two judgments for the one-third octave bands of noise for that particular test day; column three represents the normalization of the mean judgments to zero; column four represents the constant used to transfer the mean judgments to the multifilter; column five represents the interpolated settings for the multifilter used to shape the broad-band noise to the contours of each listeners dynamic range.

RESULTS

One-third octave bands. The judgments for threshold, MCL, and UCL for the third-octave bands of noise for each listener obtained during the third test session are plotted on Figures 2 to 7. The thresholds of all the listeners were within the normal range. The range for the two judgments for Day three for each listener is very small with the majority of threshold judgments being the same for both measures. All listeners thresholds fell within the range from 0 to 20dB SPL except for the 250 Hz threshold where judgments were slightly higher. This result is consistent with the ANSI S3.6-1969 standard reference zero values for normal hearing thresholds obtained with TDH-49 earphones in MX-41/AR cushions. The levels chosen as MCL by the six listeners cover a larger range than the levels chosen as threshold. Listener 1 displayed the lowest MCL's of the group, with her judgments falling between 60 and 70dB SPL for the middle and high frequencies. Listeners 2 and 5 have normal levels for comfort (between 70 and 80dB SPL). Slightly high MCL's were chosen by listeners 3 and 4 (between 80 and 90dB SPL) and listener 6 chose an extremely high MCL level for one-third octave bands of noise with her judgments falling between 90 and 102dB SPL. Judgments by all six listeners for MCL cover a range between 60 and 102dB SPL. Listener 5 had the largest range between her two judgments for MCL (22dB SPL), while listener 6 had the narrowest range (6 dB SPL) for her two judgments. The range of levels between the two judgments of MCL for the other listeners was 6 to 14dB SPL.

Listeners 4 and 5 chose normal UCL's for third-octave bands of noise (90 to 100dB SPL). The UCL levels for listeners 1,2,3 and 6 were all slightly higher than normal (between 100 and 115 dB SPL). The dynamic range for listener six shows an unusual configuration with normal threshold levels, but MCL and UCL levels that are only 5-10dB SPL apart. With the exception of listener 5, the average range for the two judgments across listeners for the UCL level is about 2 to 6dB SPL. The range of judgments for listener 5 was larger than the other listeners for both MCL and UCL judgments. For MCL, the range is between 1 and 22dB SPL, and for UCL the range is between 3 and 13dB SPL. In comparison, the range of judgments for listener six is between 0 and 6dB for MCL and 0 and 7dB SPL for UCL judgments.

The standard deviation of a single measurement of threshold, MCL or UCL was estimated by the following formula:

$$\overline{\sigma_m} = \sqrt{\frac{\sum_1^6 \left[\frac{\sum_1^8 \sigma_m^2}{8}\right]}{6}}$$

where

$$\sigma_m^2 = \frac{\sum_1^4 (\bar{x} - x)^2}{n-1}$$

This is the square root of the variance summed and averaged across eight frequencies and six listeners. This measure, σ_m^2, is given for threshold, MCL and UCL in Table 4. Also shown is the range of the square root of the average variance across listeners and across frequencies. Listener 2 displayed the largest standard deviations for threshold and falls among the larger standard deviations for MCL and UCL. Listener 3 had the largest standard deviation for MCL, followed by listener 5. Both listeners also show large ranges for their judgments for MCL on Figures 4 and 7. (one-third octave band judgments). Listener 5 has the lowest standard deviations for threshold, listener 6 has the lowest standard deviation for MCL and listener 4 has the lowest standard deviation for UCL. The highest standard deviation score for UCL belongs to listener 1. The frequency displaying the largest standard deviation is 6300 Hertz for all three measurements, with 250 and 500 Hertz also showing large standard deviations. Overall, the range of standard deviation scores is lowest for threshold than for MCL or UCL, and the ranges for MCL and UCL are about equal.

The graph shown in Figure 8 represents the mean judgments across listeners for the third-octave bands of noise for the data collected on days two and three for threshold, MCL and UCL. Included in the graph is a range of ±2 standard deviations for each frequency. Again, the range for standard deviation scores is less for threshold and larger for both MCL and UCL.

Table 4. Standard deviation and variance measures across listeners and frequencies for the third-octave bands of noise.

Threshold	Frequency (Hz)								across (listeners)	
Listeners	250	500	1000	1600	2000	3150	4000	6300	mean variance	Stand. dev.
1	8.7	3.3	5.7	9.7	7.0	3.6	0.7	21.7	7.6	2.7
2	37.6	9.7	7.6	1.6	1.6	3.3	10.9	12.0	10.5	3.2
3	4.7	6.7	8.7	3.6	0.3	4.3	2.9	2.9	4.3	2.1
4	2.0	2.9	1.6	8.9	6.7	1.7	4.3	2.9	3.9	2.0
5	8.7	1.6	2.9	4.9	1.6	3.0	4.7	1.7	3.6	1.9
6	2.9	6.7	0.3	2.9	2.9	3.3	9.6	10.7	4.9	2.2
mean variance (Freq's)	10.8	5.2	4.5	5.3	3.4	3.2	5.5	8.7	5.8	
stand. dev.	3.3	2.3	2.1	2.3	1.8	1.8	2.3	2.9		$\boxed{2.4}$ dB

MCL	250	500	1000	1600	2000	3150	4000	6300	mean variance	standard deviation
1	25.7	88.0	16.7	14.7	11.7	7.0	25.0	12.9	25.2	5.0
2	4.3	36.3	54.0	36.7	49.7	19.6	8.3	90.9	37.5	6.1
3	56.9	74.3	98.9	94.3	50.3	60.3	99.0	36.9	71.4	8.4
4	11.7	7.6	12.0	17.6	28.0	12.0	14.3	6.0	13.7	3.7
5	64.9	103.0	18.0	31.3	56.3	20.7	9.7	170.0	59.2	7.7
6	1.3	8.3	2.9	5.7	1.6	6.3	8.3	17.7	6.5	2.6
mean variance (Freq)	27.6	52.9	33.8	33.4	32.9	21.0	27.4	55.7	35.6	
stan. dev. (Freq)	5.3	7.3	5.8	5.8	5.7	4.6	5.2	7.5		$\boxed{6.0}$ dB

UCL	250	500	1000	1600	2000	3150	4000	6300	mean variance	standard deviation
1	40.0	78.3	106.3	70.9	52.9	46.3	56.9	56.3	63.5	8.0
2	4.0	8.3	26.3	8.7	4.3	8.3	22.7	60.9	17.9	4.2
3	2.3	9.0	24.9	13.7	8.3	0.9	2.3	1.0	7.8	2.8
4	13.3	3.6	3.7	3.7	3.7	0	2.7	23.6	6.8	2.6
5	11.7	11.6	15.0	19.6	9.7	15.0	21.0	30.9	14.4	3.8
6	30.0	28.0	28.9	11.3	4.7	16.3	26.9	32.7	22.4	4.7
mean variance (Freq)	16.9	23.1	34.2	21.3	13.9	14.5	18.9	34.2	22.1	
stan dev. (Freq)	4.1	4.8	5.8	4.6	3.7	3.8	4.3	5.9		$\boxed{4.7}$ dB

Figure 2. Listener 1- Threshold, MCL and UCL judgments for third-octave bands of noise.

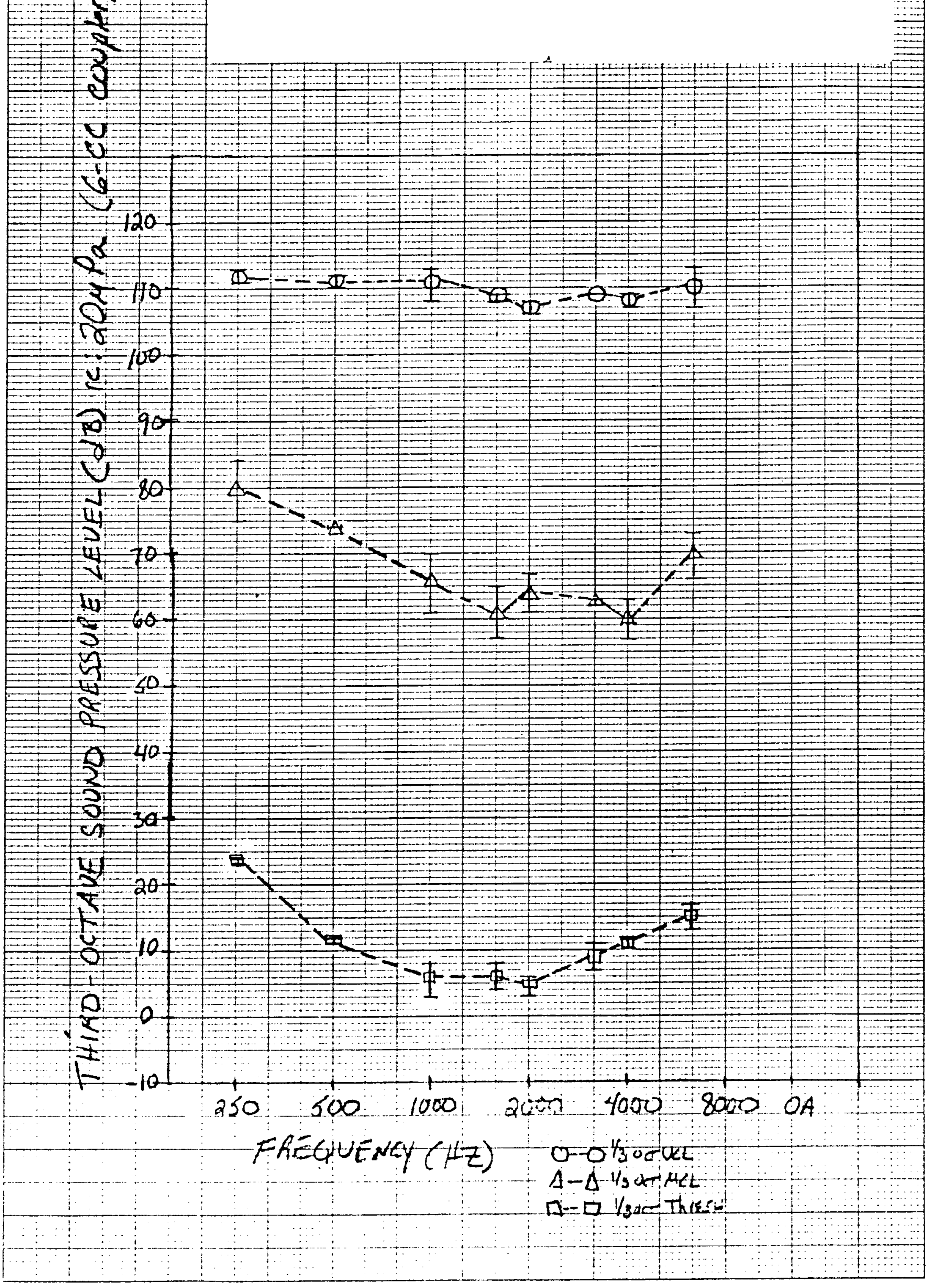


Figure 3. Listener 2- Threshold, MCL and UCL judgments for third-octave bands of noise.

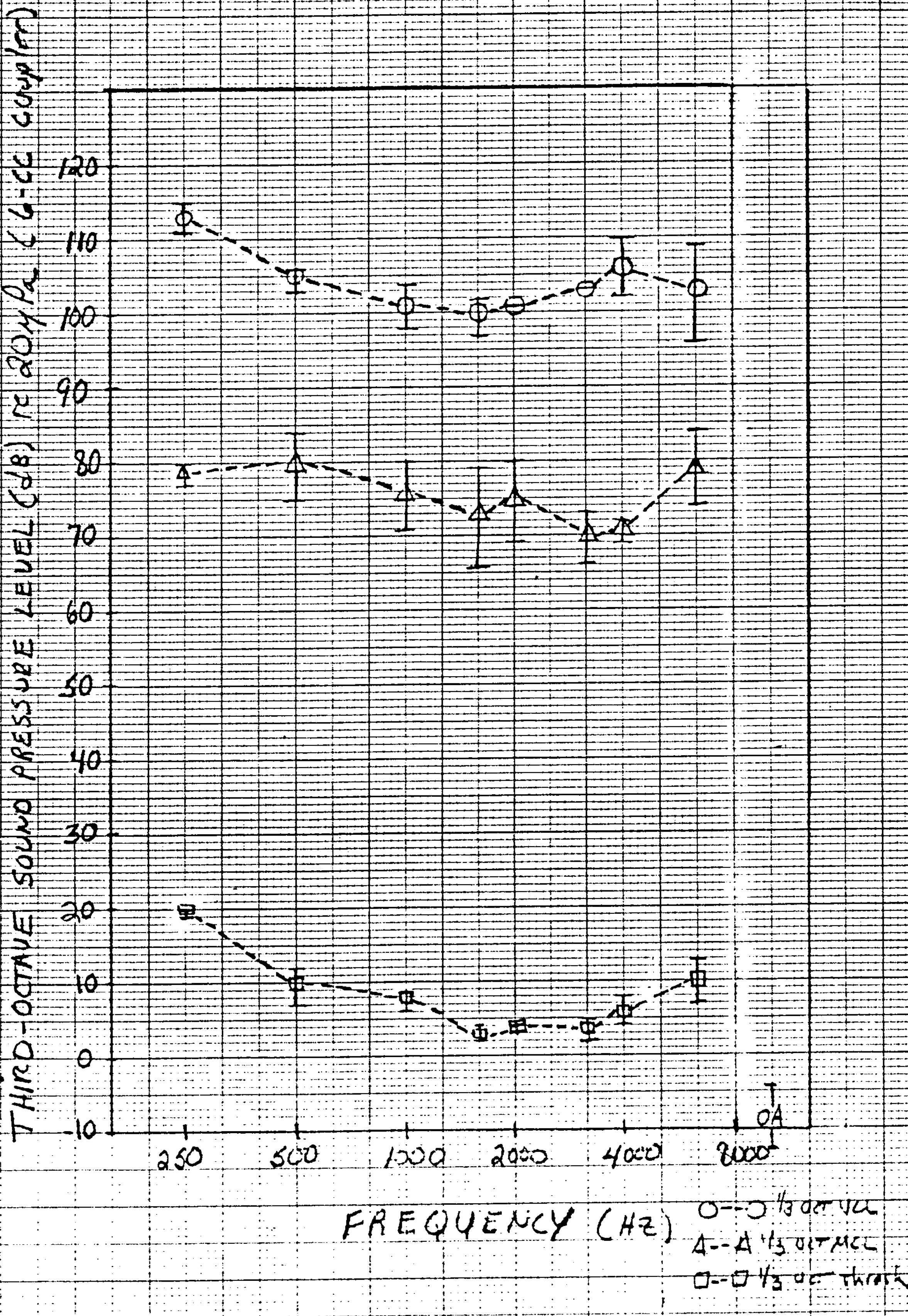


Figure 4. Listener 3- Threshold, MCL and UCL judgments for third-octave bands of noise.

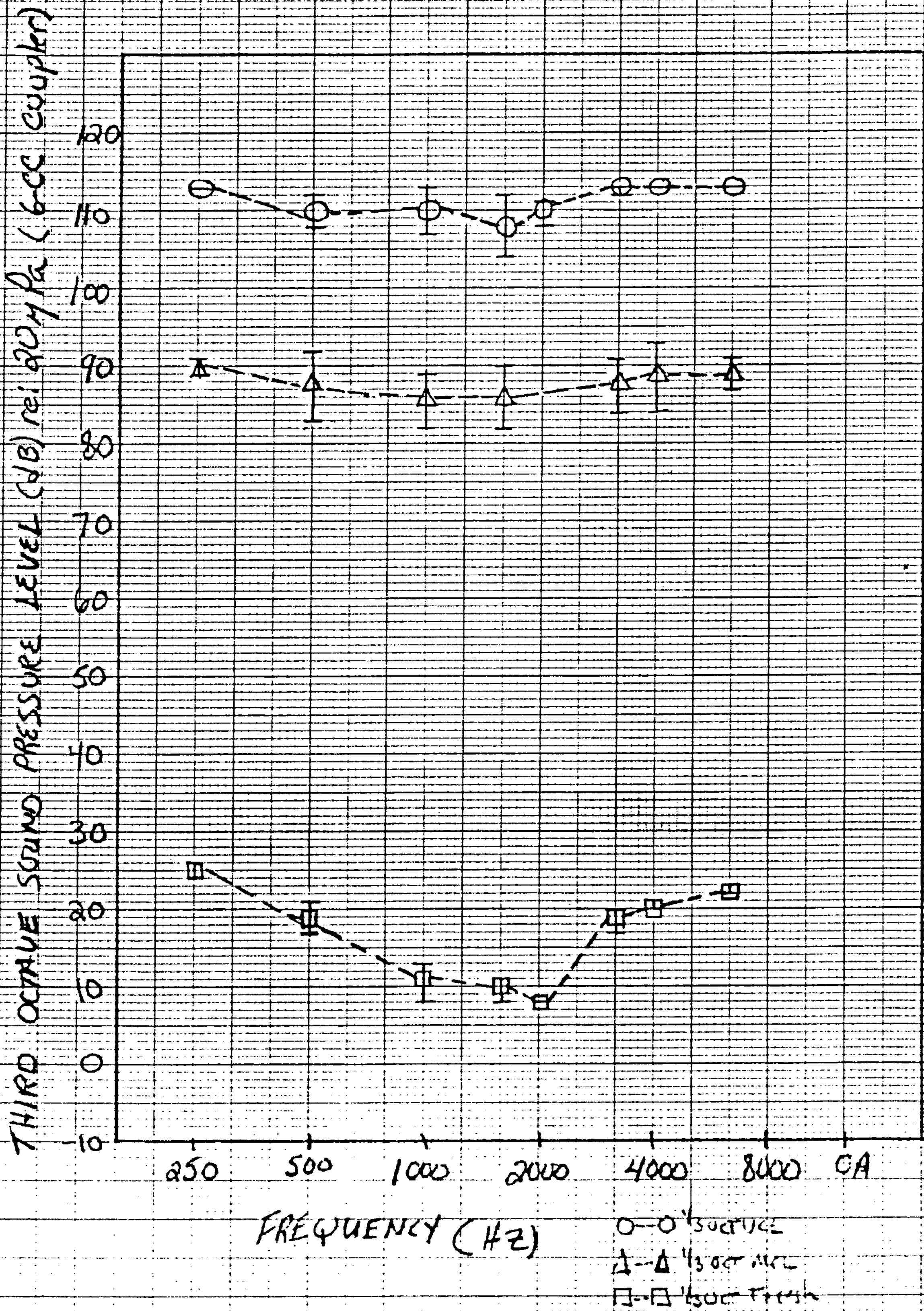


Figure 5. Listener 4- Threshold, MCL and UCL judgments for third-octave bands of noise.

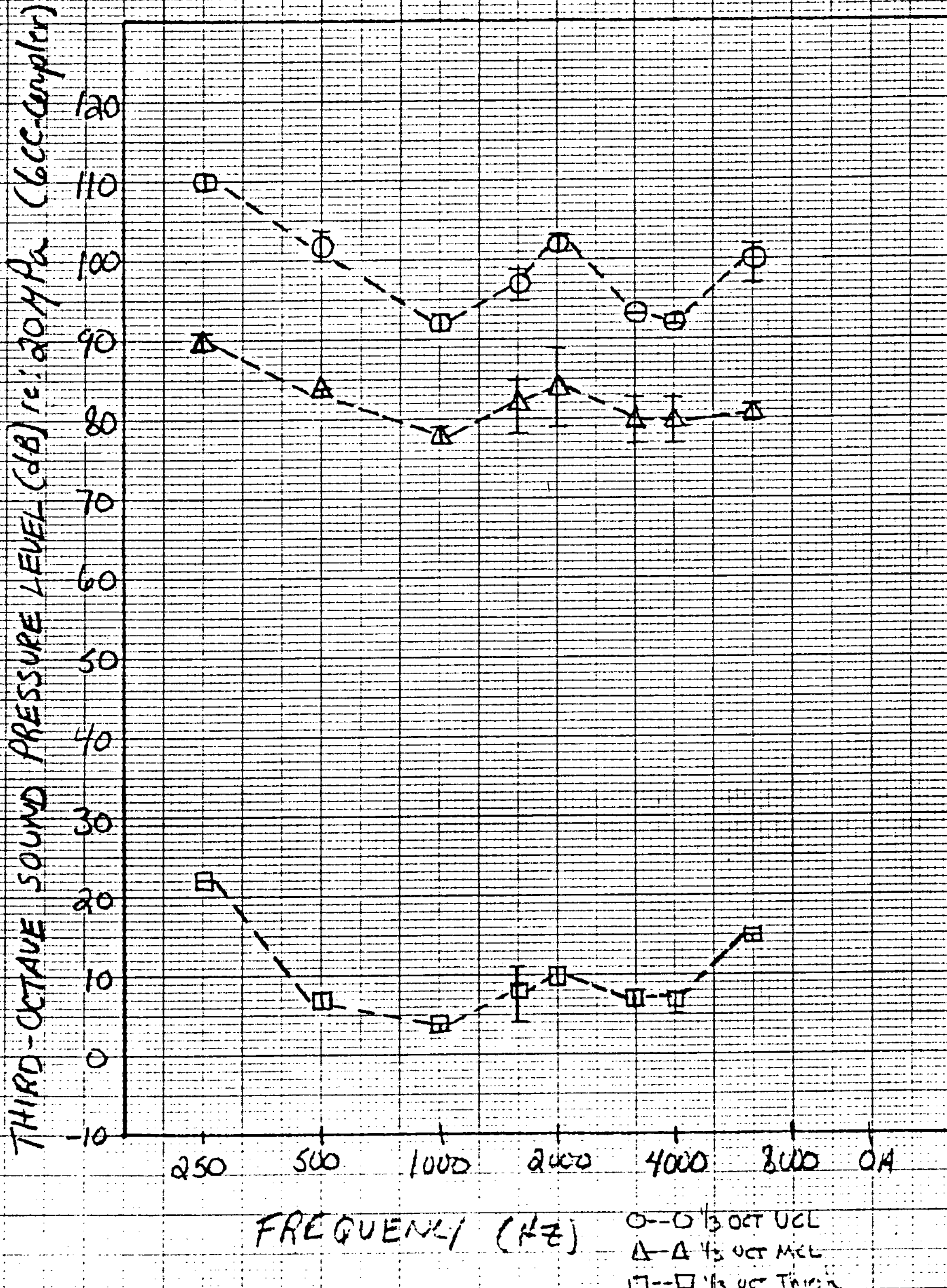


Figure 6. Listener 5- Threshold, MCL and UCL judgments for third-octave bands of noise.

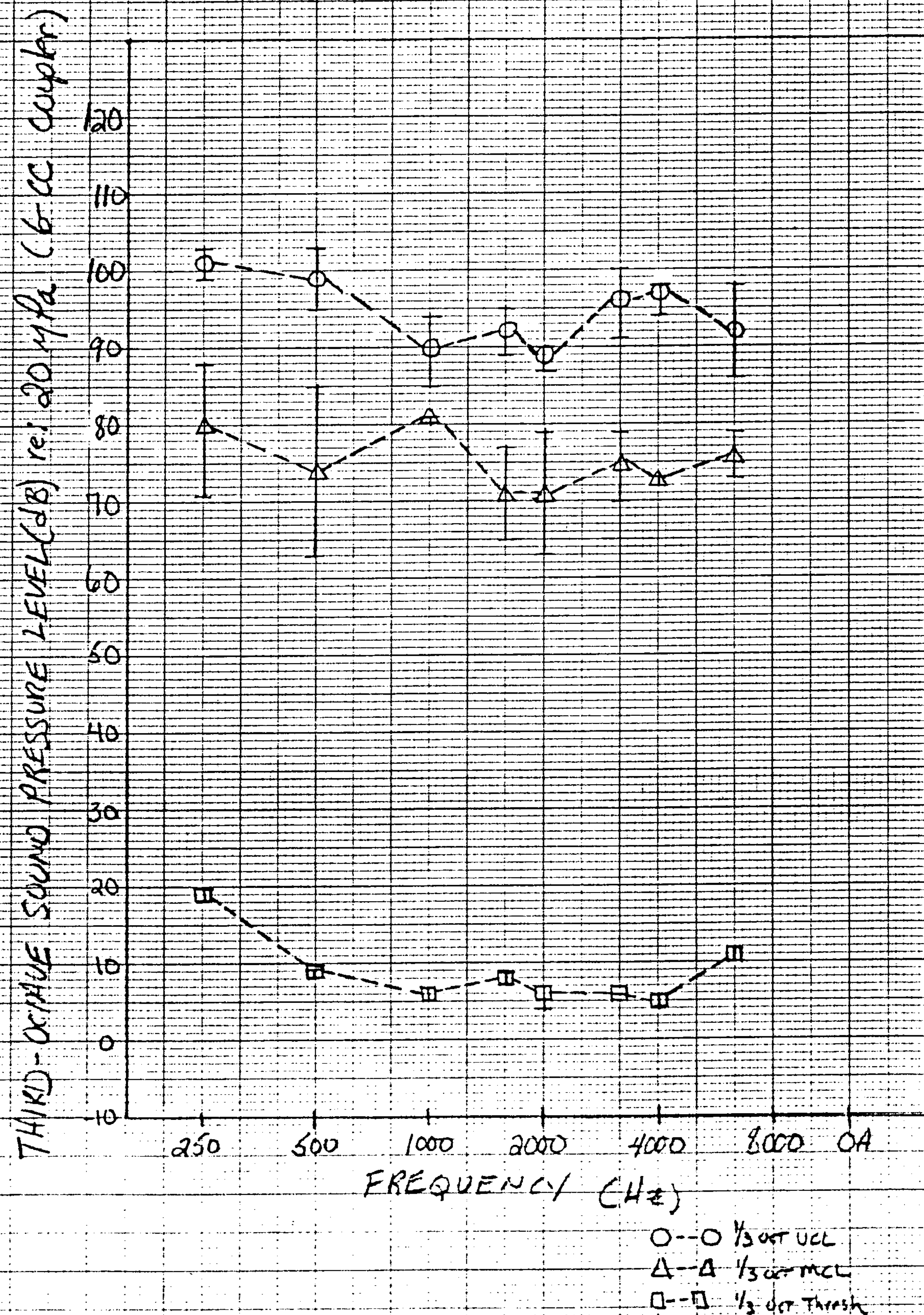


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Figure 7. Listener 6- Threshold, MCL and UCL judgments for third-octave bands of noise.

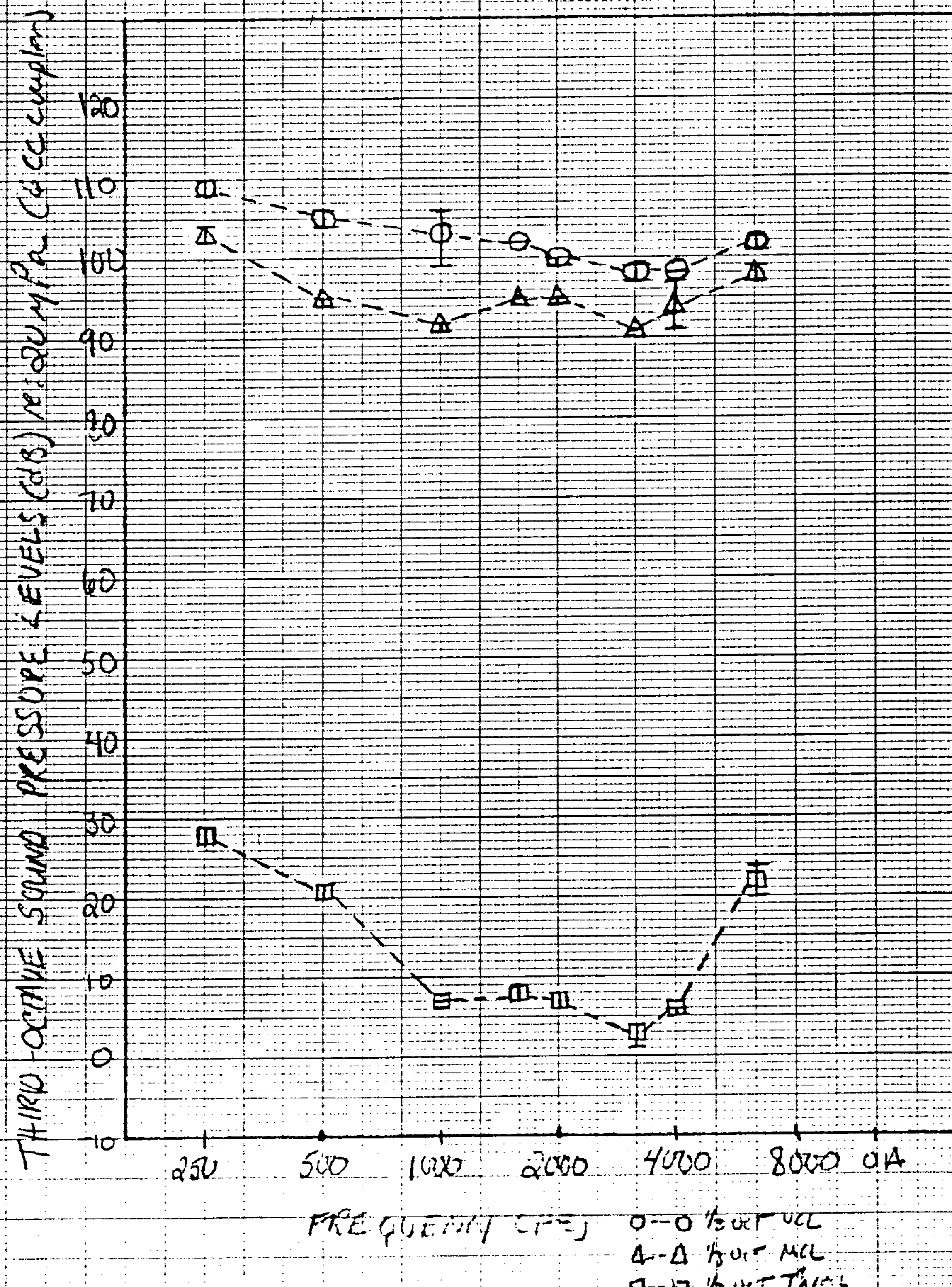
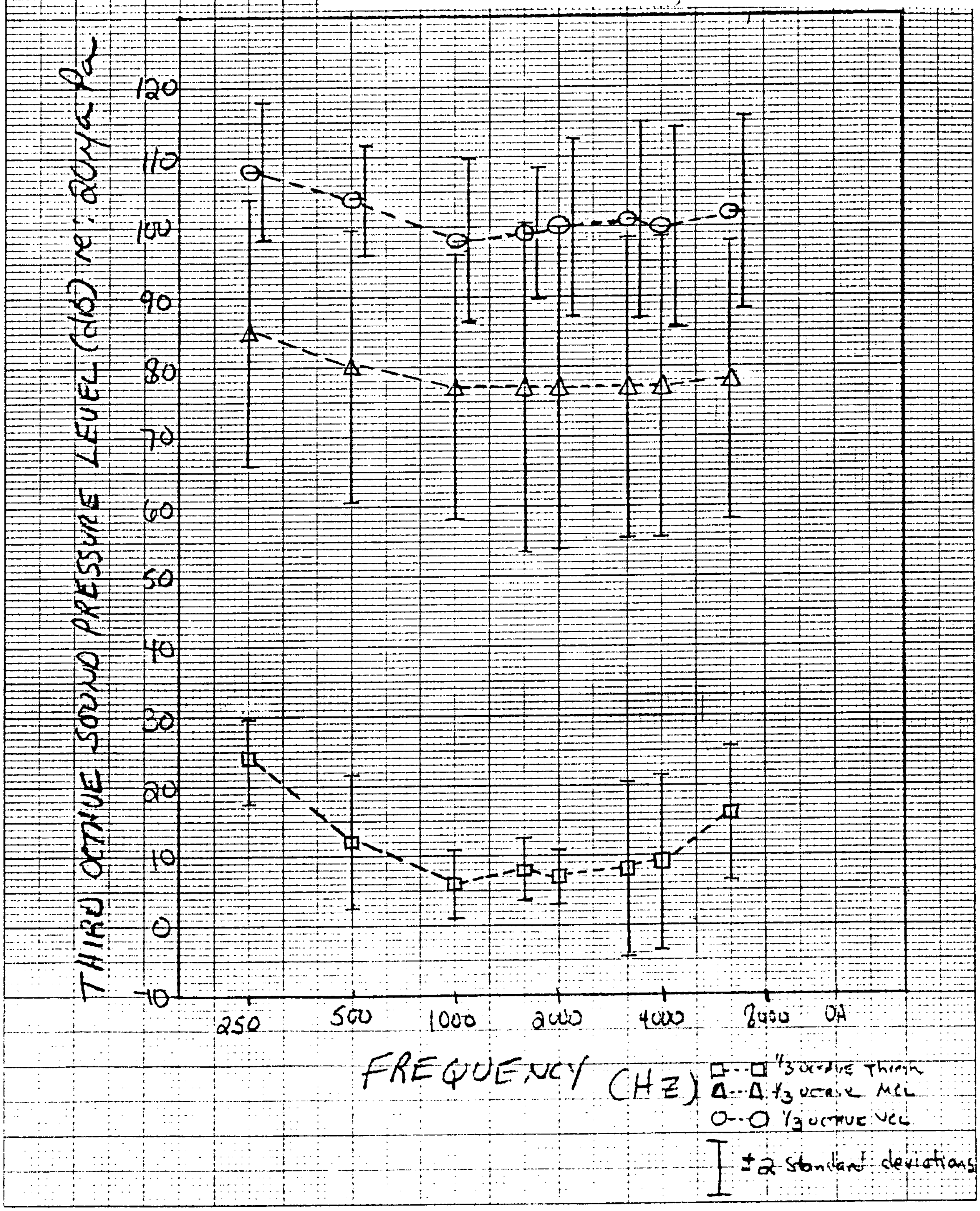


Figure 8. Mean judgments for threshold, MCL and UCL for third-octave bands of noise across all six listeners. Graph is shown with a range of ±2 standard deviations.



<u>Broad-Band Noise Stimulus</u>. Each listener's data for both the third-octave bands of noise and the broad-band noise for Day 3 are shown on Figures 9 to 14. This graph is arranged in the following manner: threshold judgments from the threshold-shaped broad-band noise data; MCL judgments from the MCL-shaped broad-band noise data; UCL judgments from the UCL-shaped broad-band noise data. These measurements are plotted on the same graph as the one-third octave band judgments for each listener's dynamic range. The judgments for the threshold-shaped broad-band noise data, the MCL-shaped broad-band noise data and the UCL-shaped broad-band noise data for threshold, MCL and UCL are shown for each listener in Figures 15 through 32.

The broad-band noise data is plotted on the same graph with the one-third octave noiseband judgments for threshold, MCL and UCL to visually compare the two sets of measurements for the purpose of detecting the presence or absence of loudness summation for the broad-band stimulus. Loudness summation is seen on the graph as a difference between the corresponding physical measurements of one-third octave bands and broad-band stimuli so that the broad-band noise measurements are at a lower sound pressure level than the individual one-third octave band judgments.

Each graph of broad-band noise data also includes a mean measure of the overall sound pressure level present for each shaped broad-band contour associated with the two judgments made for each shaping. The overall sound pressure level was determined

1/3 octave band judgments
Threshold, MCL, UCL

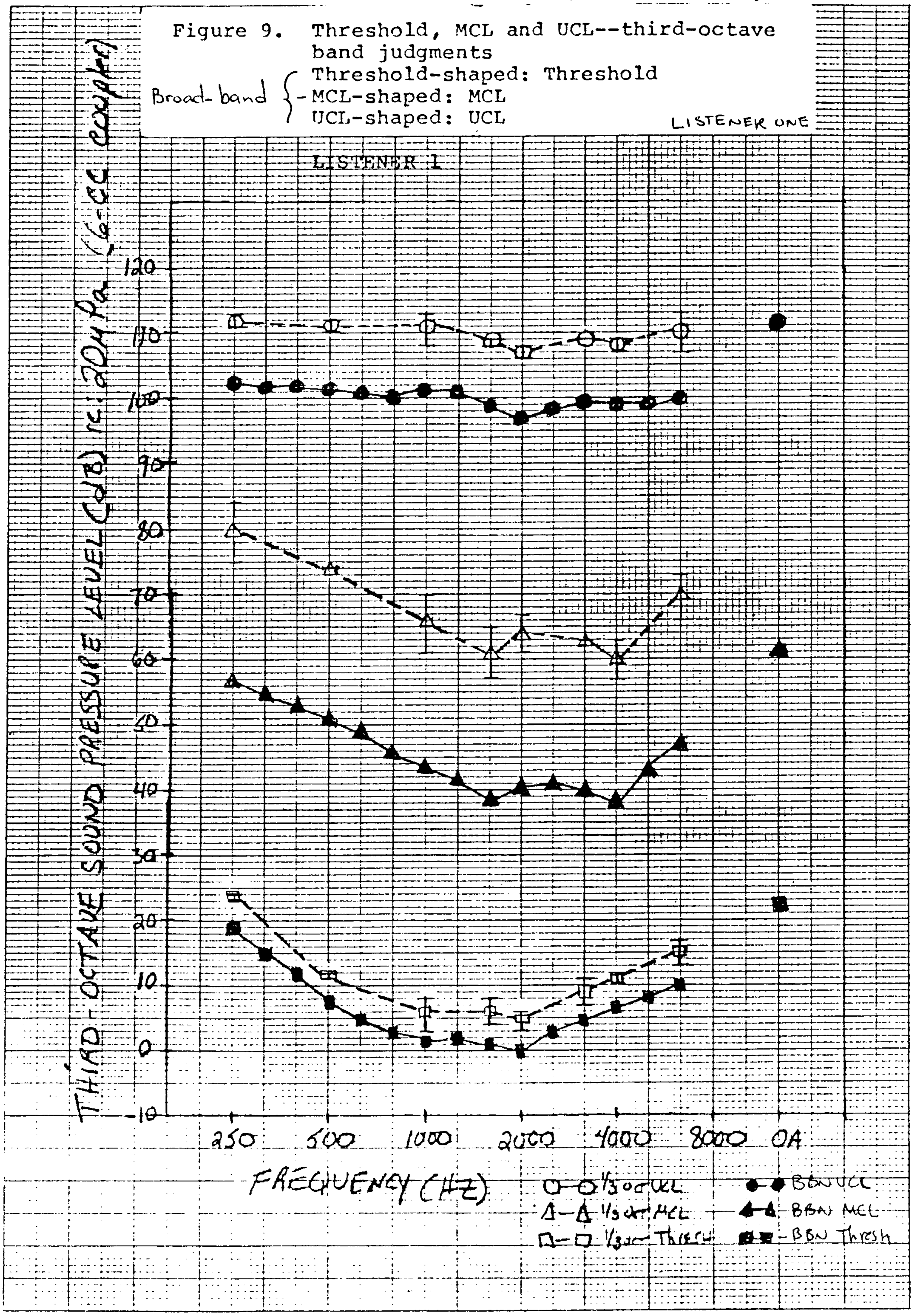


Figure 9. Threshold, MCL and UCL--third-octave band judgments
Broad-band: Threshold-shaped: Threshold; MCL-shaped: MCL; UCL-shaped: UCL

Figure 10. Threshold, MCL and UCL judgments
for third-octave bands of noise
-Threshold-shaped: threshold
broad-band:-MCL-shaped: MCL judgment
-UCL-shaped: UCL judgment

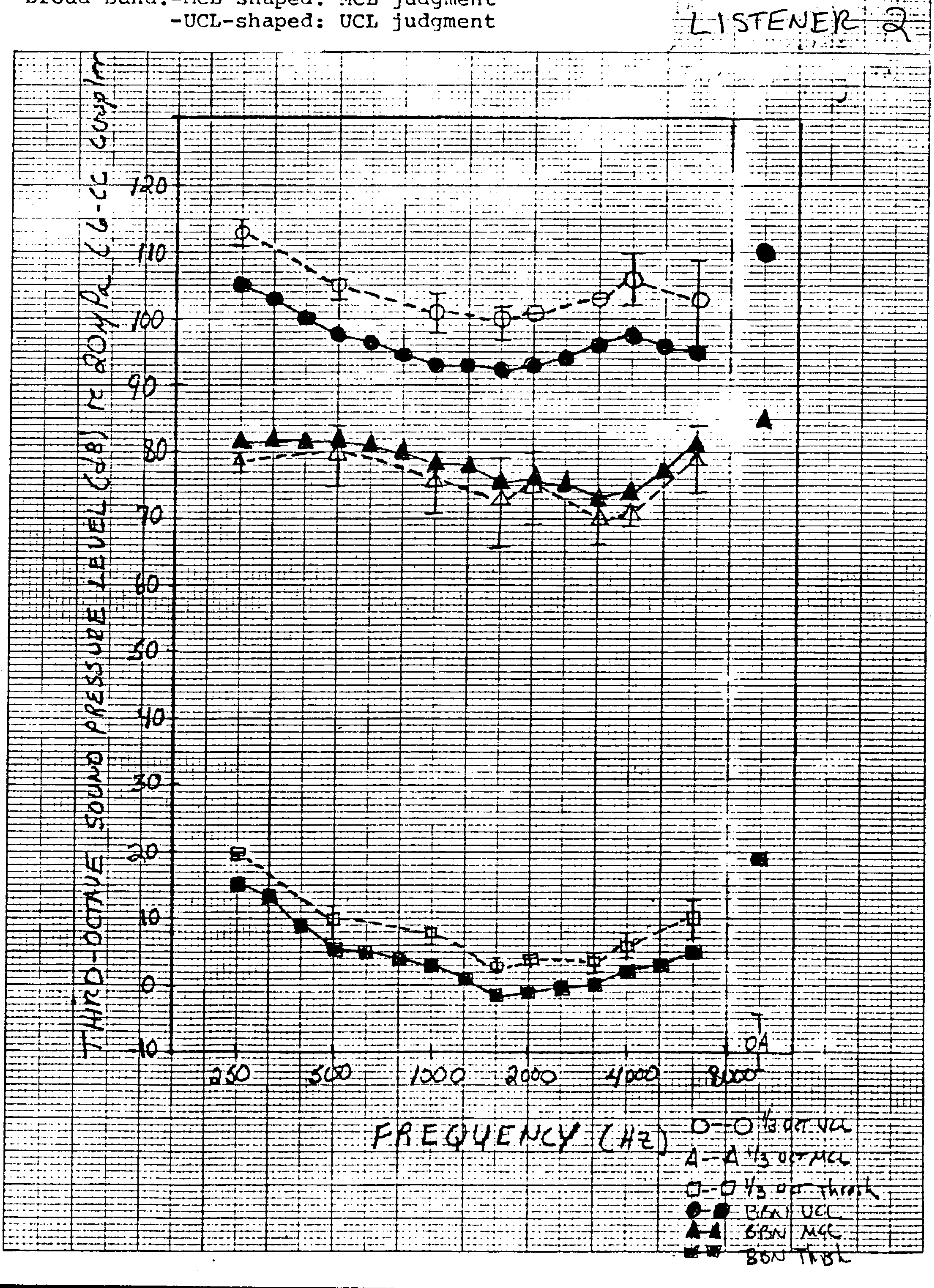


Figure 11. Threshold, MCL and UCL judgments
for third-octave bands of noise
- Threshold-shaped: threshold
broad-band- MCL-shaped: MCL judgment
- UCL-shaped: UCL judgment

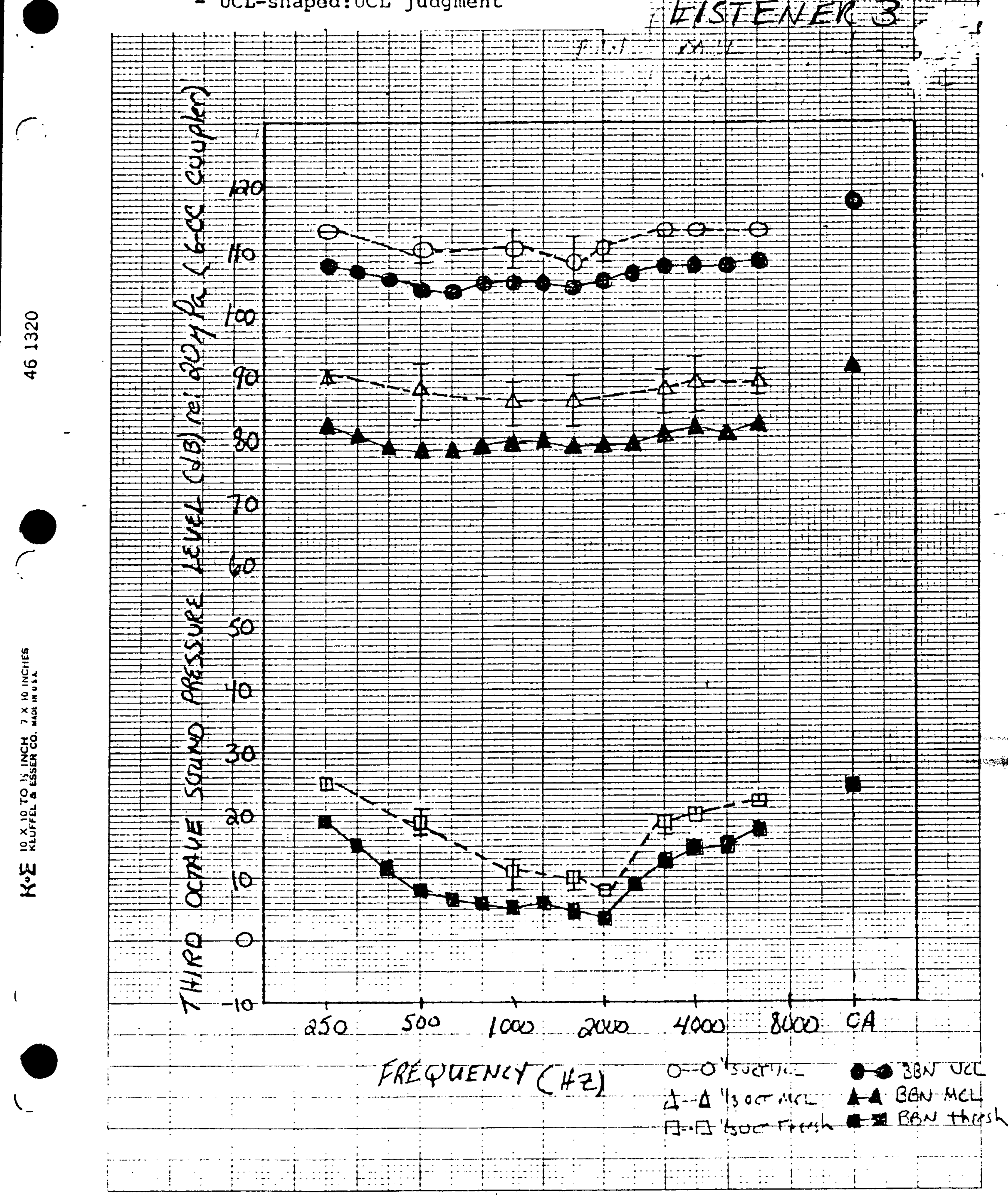


Figure 12. Threshold, MCL and UCL judgments for third-octave bands of noise.
- Threshold-shaped: threshold
broad-band- MCL-shaped: MCL judgment
- UCL-shaped: UCL judgment

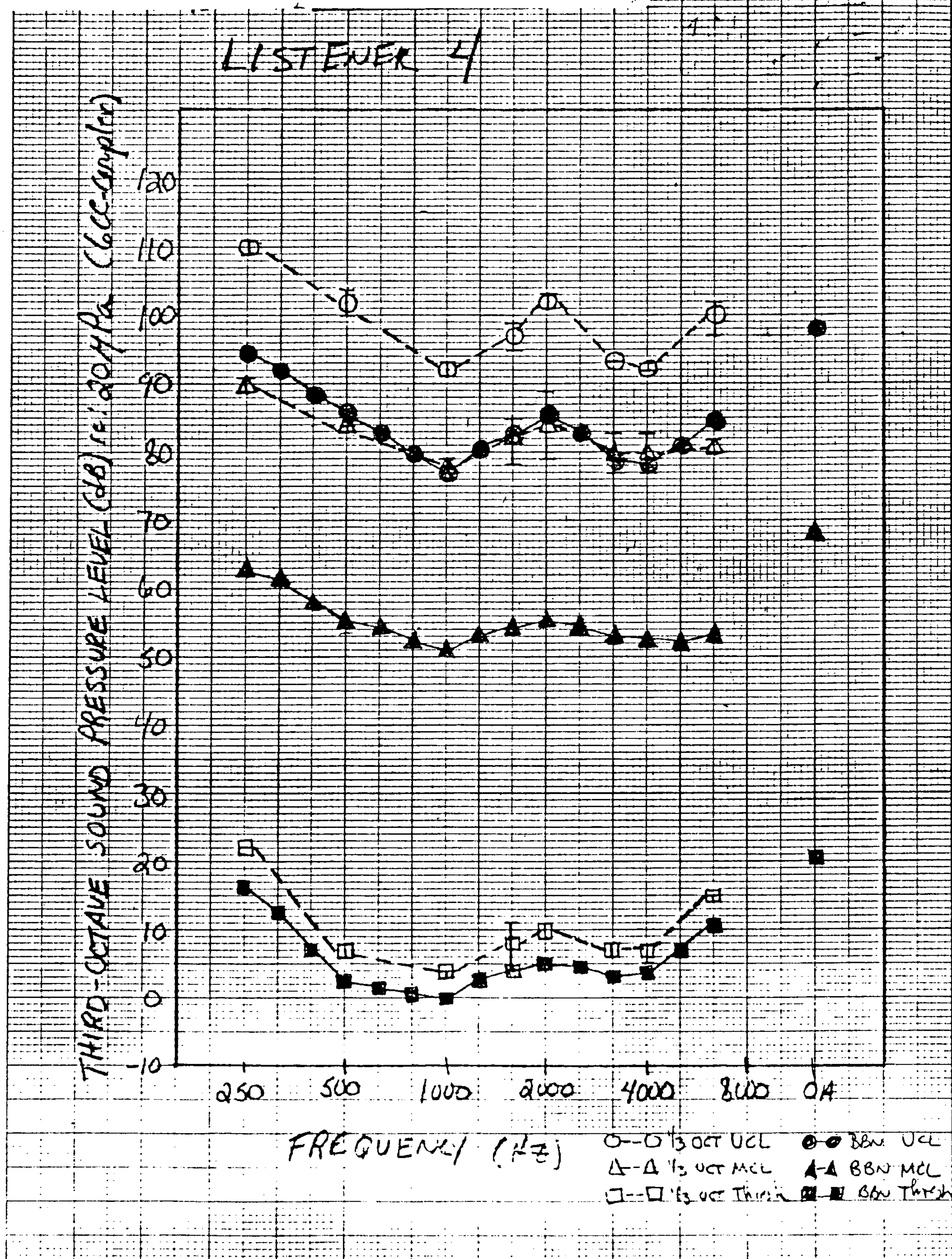
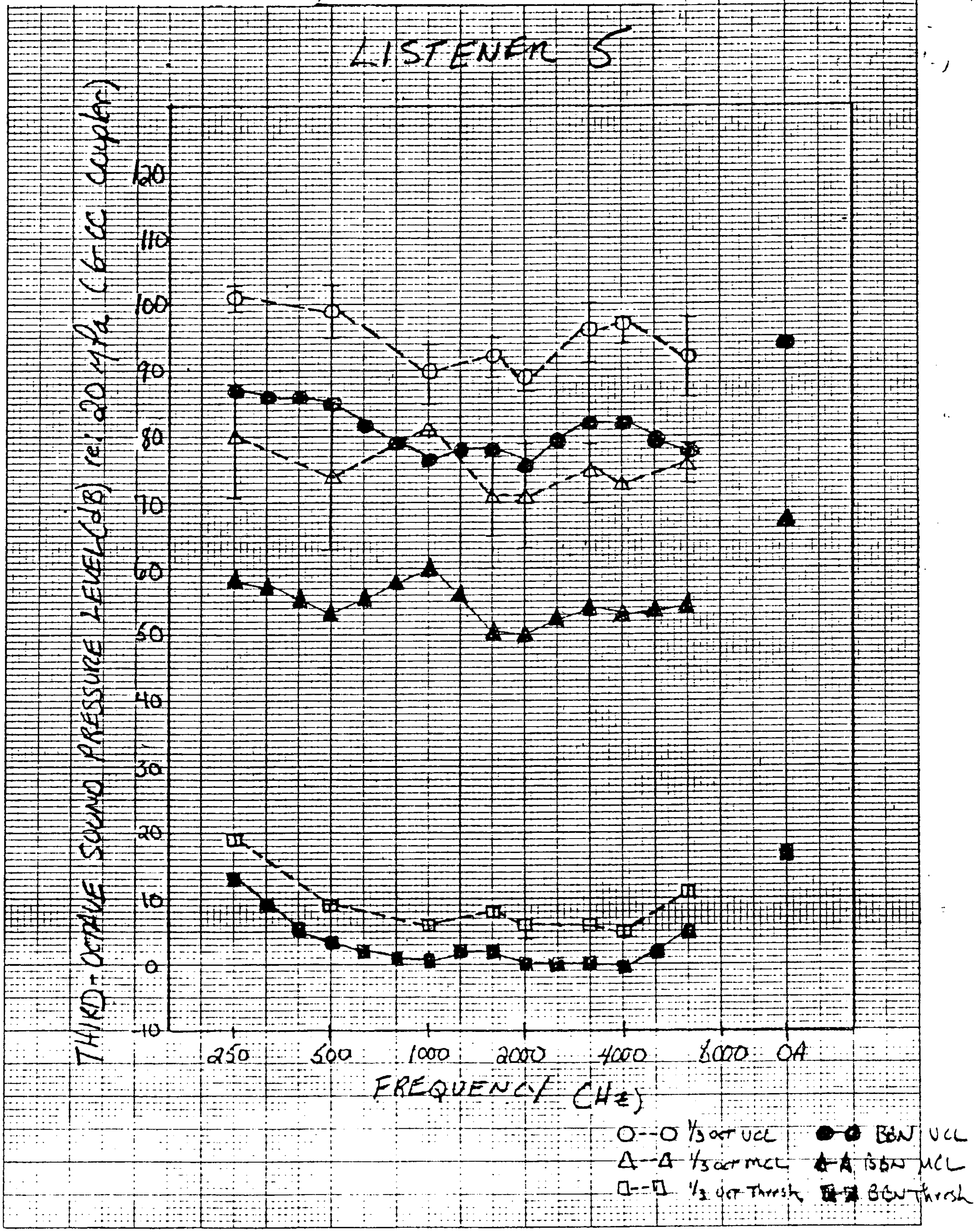


Figure 13. Threshold, MCL and UCL judgments for third-octave bands of noise.
- Threshold-shaped: threshold
broad-band- MCL-shaped: MCL judgment
- UCL-shaped: UCL judgment



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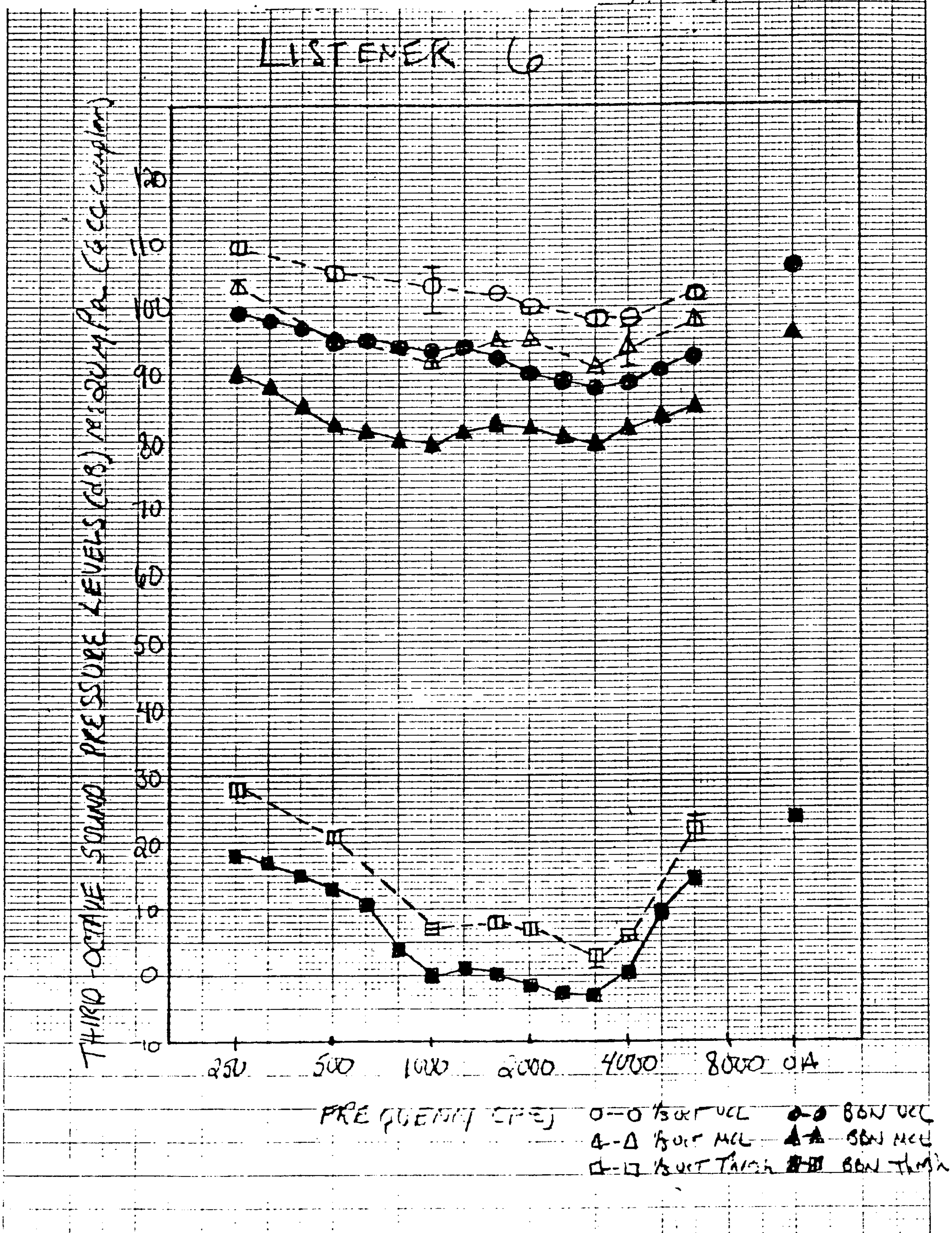
K-E 10 X 10 TO 1/2 INCH 7 X 10 INCHES KEUFFEL & ESSER CO. MADE IN U.S.A.

Figure 14. Threshold, MCL and UCL judgments for third-octave bands of noise.
- Threshold-shaped: threshold
broad-band- MCL-shaped: MCL judgment
= UCL-shaped: UCL judgment



by the amount of attenuation introduced into the system. This overall level of attenuation was determined by taking the mean of the set of judgments made by each listener for the threshold, MCL and UCL broad-band shaped contour. Two judgments of threshold, MCL and UCL were made for each of the three shapings for each test day. These judgments are shown in Table 5.

<u>Variability of Judgments</u>. The standard deviation of a single measurement of threshold, MCL and UCL for the broad-band noise was estimated by the following formula:

$$\overline{\sigma_m} = \sqrt{\frac{\sum_1^6 \left[\frac{\sum_1^6 \sigma_m^2}{12}\right]}{6}}$$

$$\text{where } \sigma_m^2 = \frac{\sum_1^2 (\bar{x}-x)^2}{n-1}$$

This is the square root of the variance summed across listeners and two test days for three different shapings of the broad-band noise. The measure, σ_m^2, was based on the two judgments on one day instead of two days. The measure, σ_m^2, is given for the threshold, MCL and UCL judgments in Table 6. Listener 2 shows the highest mean standard deviation for threshold, while listener 1 has the highest mean standard deviations for MCL and UCL. Listener 1 has the low score for threshold and listener 4 has the low score for MCL and UCL.

Table 5. Judgments of threshold, MCL and UCL for the shaped broad-band noise. Two judgments were made for each shaped contour for each day.

		Threshold Shaping				MCL Shaping				UCL Shaping			
		Day two		Day Three		Day two		Day three		Day two		Day three	
Listener	Judgment	1	2	1	2	1	2	1	2	1	2	1	2
1	Thresh	102	100	105	105	108	109	109	109	107	108	109	111
	MCL	62	61	64	69	66	69	65	73	60	73	71	71
	UCL	31	29	14	11	22	20	15	15	33	21	16	13
2	Thresh	112	100	109	110	105	110	114	115	107	111	111	113
	MCL	47	52	50	48	49	44	37	38	52	48	44	37
	UCL	10	10	17	14	16	16	22	22	18	15	17	16
3	Thresh	105	101	103	103	105	106	105	106	106	106	106	106
	MCL	53	52	39	34	57	48	36	31	58	67	46	48
	UCL	17	16	8	6	16	13	11	9	16	16	8	8
4	Thresh	108	106	109	107	112	112	110	108	112	113	111	110
	MCL	66	64	58	60	66	65	60	56	58	62	66	66
	UCL	28	26	28	28	28	26	26	27	30	28	30	28
5	Thresh	108	110	109	108	117	115	116	118	112	112	110	109
	MCL	47	48	47	43	68	70	60	60	40	54	51	49
	UCL	30	32	26	26	36	32	36	33	32	34	32	34
6	Thresh	105	105	106	103	111	112	108	105	110	111	110	109
	MCL	34	29	32	32	44	35	30	28	34	30	29	25
	UCL	22	18	24	24	23	20	18	18	16	16	20	20

Table 6. Standard deviation and variance measures across listeners and broad-band shapings for the broad-band noise.

Threshold

Listeners	Threshold Shaping DAY 1	Threshold Shaping DAY 2	MCL Shaping DAY 1	MCL Shaping DAY 2	UCL Shaping DAY 1	UCL Shaping DAY 2	Mean Variance (listeners)	mean standard deviation (listeners)
1	2.0	0	0.5	0	0.5	2.0	0.8	0.9
2	72	0.5	12.5	0.5	8.0	2.0	15.9	4.0
3	8.0	0	0.5	0.5	0	0	1.5	1.2
4	2.0	2.0	0	2.0	0.5	0.5	1.2	1.1
5	2.0	0.5	2.0	2.0	0	0.5	1.2	1.1
6	0	4.5	0.5	4.5	0.5	0.5	1.8	1.3
mean variance (shaping)	14.3	1.3	2.7	1.6	1.6	0.9	3.7	
mean S.D. (shaping)	3.8	1.1	1.6	1.3	1.3	1.0		$\boxed{1.9}$ dB

MCL

Listeners	Threshold Shaping DAY 1	Threshold Shaping DAY 2	MCL Shaping DAY 1	MCL Shaping DAY 2	UCL Shaping DAY 1	UCL Shaping DAY 2	Mean Variance (listeners)	mean standard deviation (listeners)
1	0.5	12.5	4.5	32.0	84.5	0	22.3	4.7
2	12.5	2.0	12.5	0.5	8.0	24.5	10.0	3.2
3	0.5	12.5	40.5	12.5	40.5	2.0	18.1	4.3
4	2.0	2.0	0.5	8.0	8.0	0	3.4	1.8
5	0.5	8.0	2.0	0	98.0	2.0	18.4	4.3
6	12.5	0	40.5	2.0	8.0	8.0	11.8	3.4
mean variance (shaping)	4.8	6.2	16.8	9.2	41.2	6.1	14.0	
mean S.D (shaping)	2.2	2.5	4.1	3.0	6.4	2.5		$\boxed{3.7}$ dB

UCL

Listeners	Threshold Shaping DAY 1	Threshold Shaping DAY 2	MCL Shaping DAY 1	MCL Shaping DAY 2	UCL Shaping DAY 1	UCL Shaping DAY 2	Mean Variance (listeners)	mean standard deviation (listeners)
1	2.0	4.5	2.0	0	72.0	4.5	14.2	3.8
2	0	4.5	0	0	4.5	0.5	1.6	1.3
3	0.5	2.0	4.5	2.0	0	0	1.5	1.2
4	2.0	0	2.0	0.5	2.0	2.0	1.4	1.2
5	2.0	0	8.0	4.5	2.0	2.0	3.1	1.8
6	8.0	0	4.5	0	0	0	2.1	1.4
mean variance (shaping)	2.4	1.8	3.5	1.2	13.4	1.5	4.0	
mean S.D. (shaping)	1.6	1.4	1.9	1.1	3.7	1.2		$\boxed{2.0}$ dB

Figure 15. Third-octave bands of noise and threshold-shaped judgments for threshold, MCL and UCL. For broad-band noise.

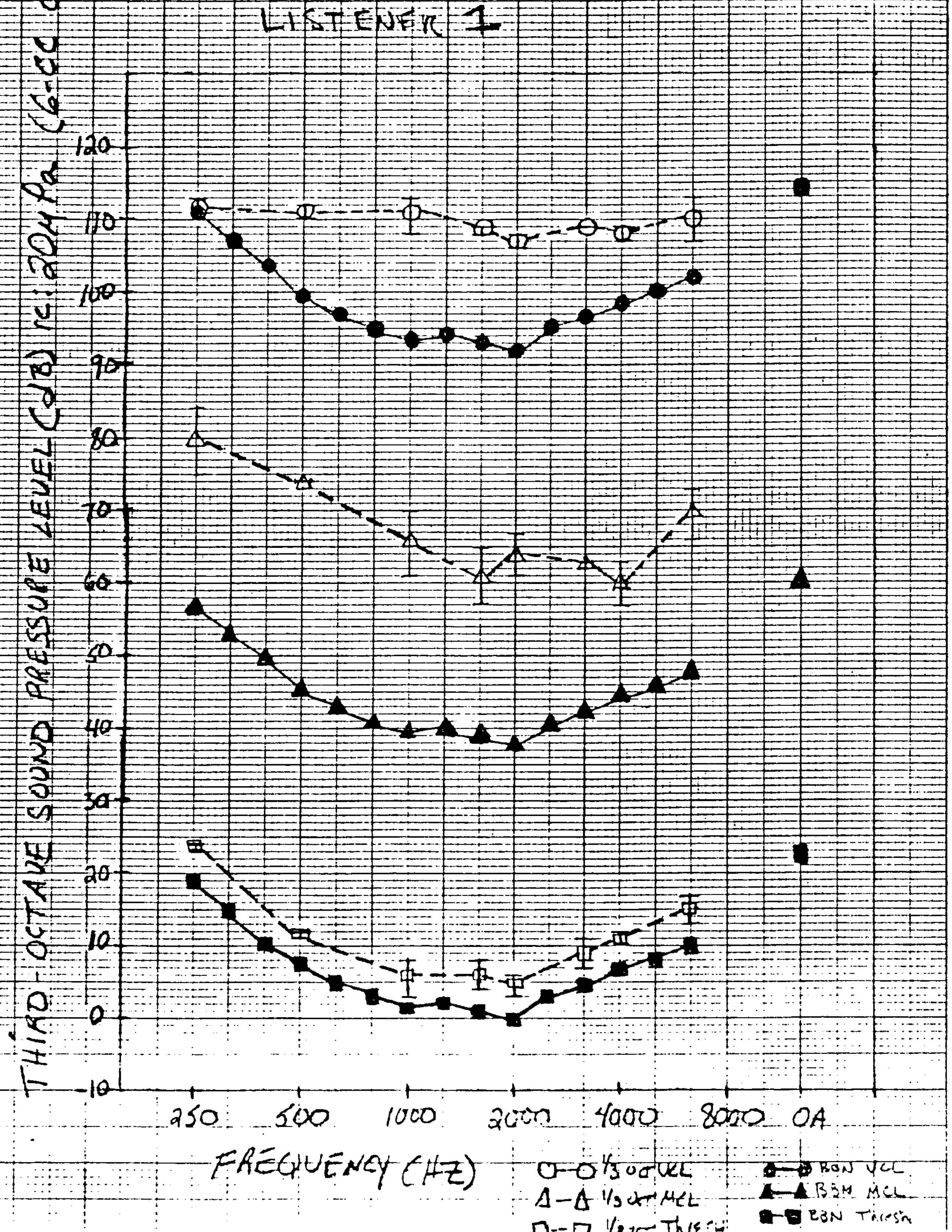


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Figure 16. Third-octave bands of noise and MCL-shaped judgments of threshold, MCL and UCL. for broad-band noise.

LISTENER ONE

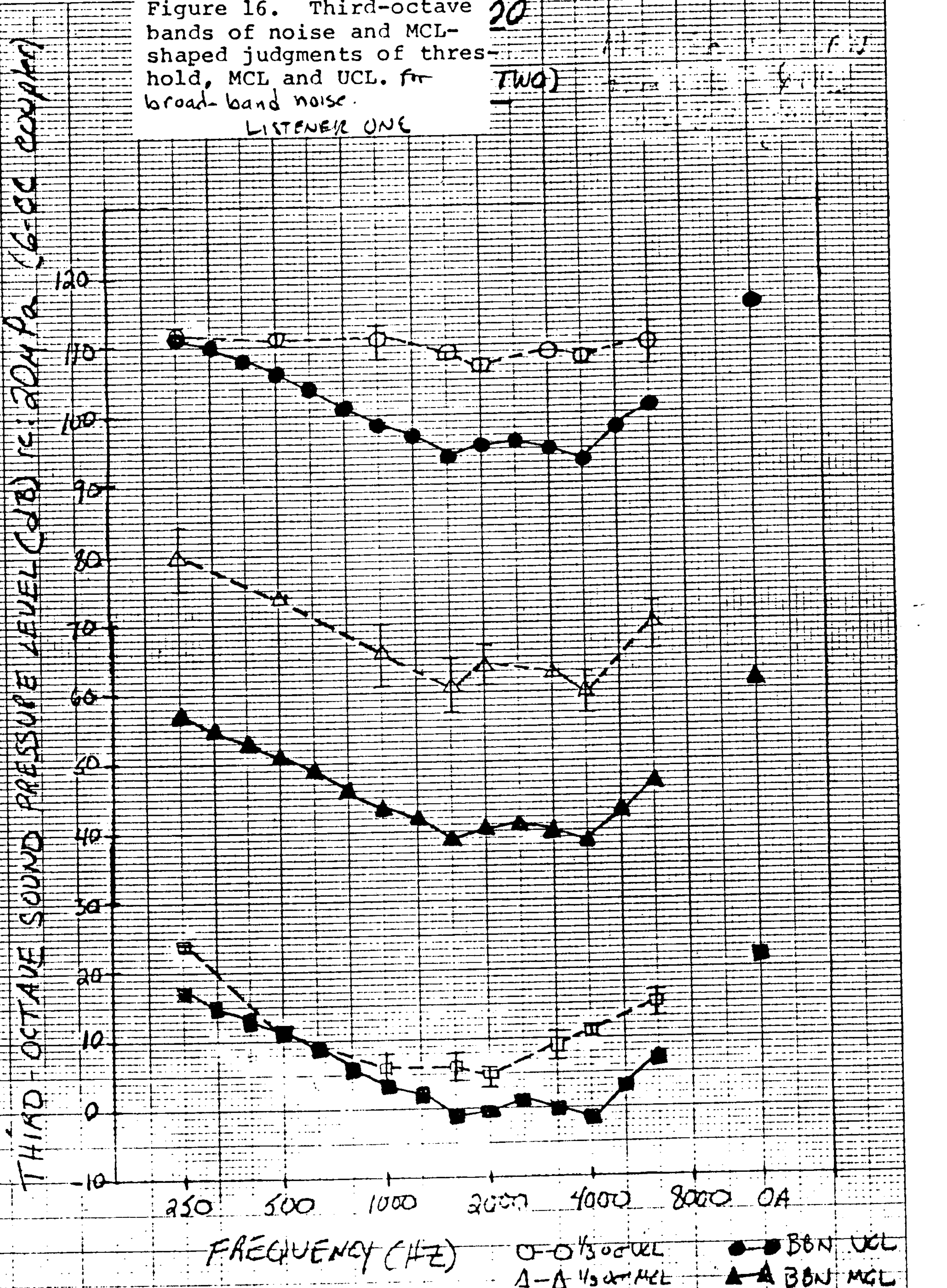

Figure 17. Third-octave bands of noise and UCL-shaped judgments of threshold, MCL and UCL. for broad-band noise
LISTENER 1

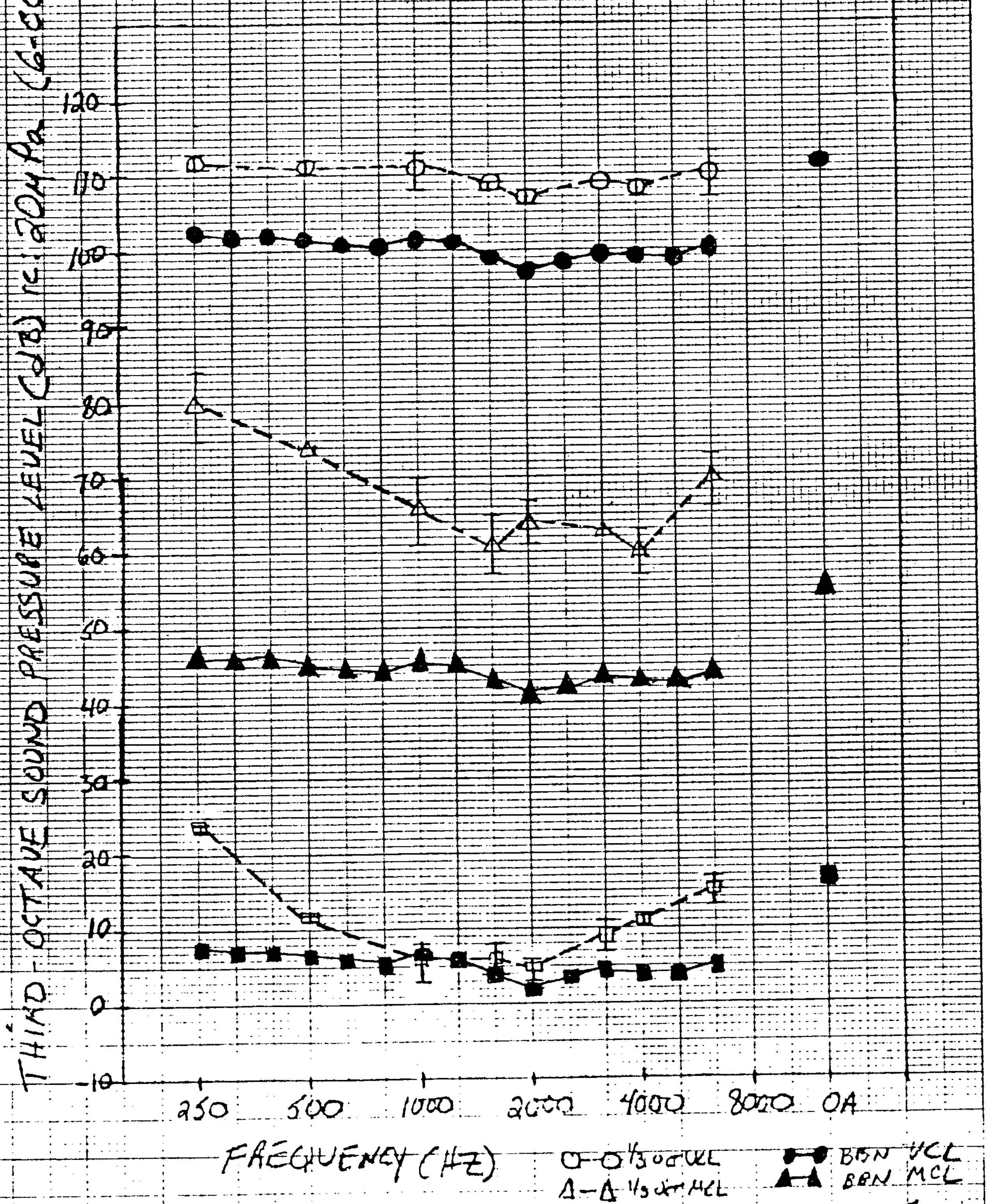

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Figure 18. Third-octave bands of noise and threshold-shaped judgments of threshold, MCL and UCL. for broad-band noise.

LISTENER 2

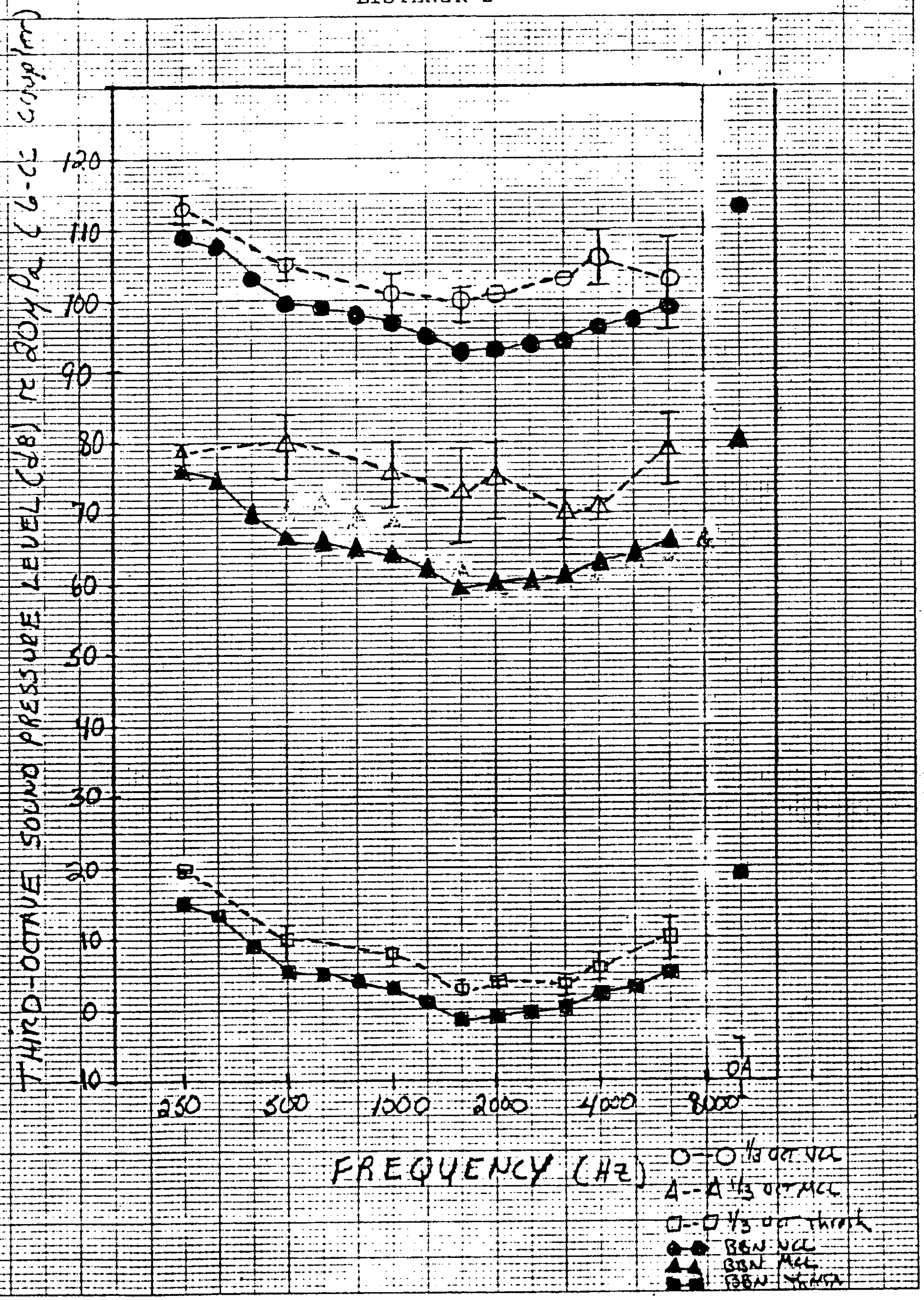

Figure 19. Third-octave bands of noise and MCL-shaped judgments of threshold, MCL and UCL. for broad-band noise.

LISTENER 2

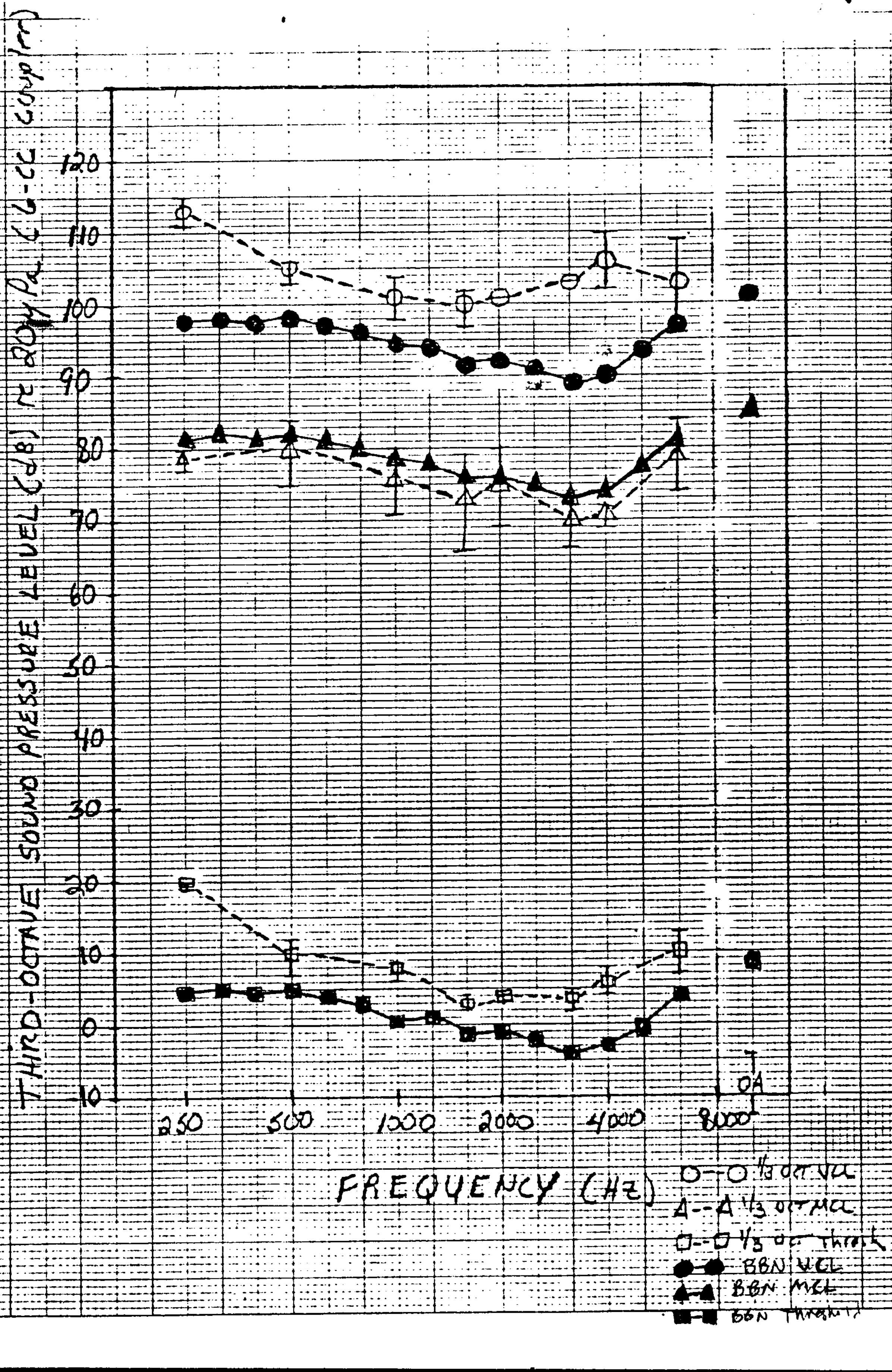

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Figure 20. Third-octave bands of noise and UCL-shaped judgments of threshold, MCL and UCL for broad-band noise.

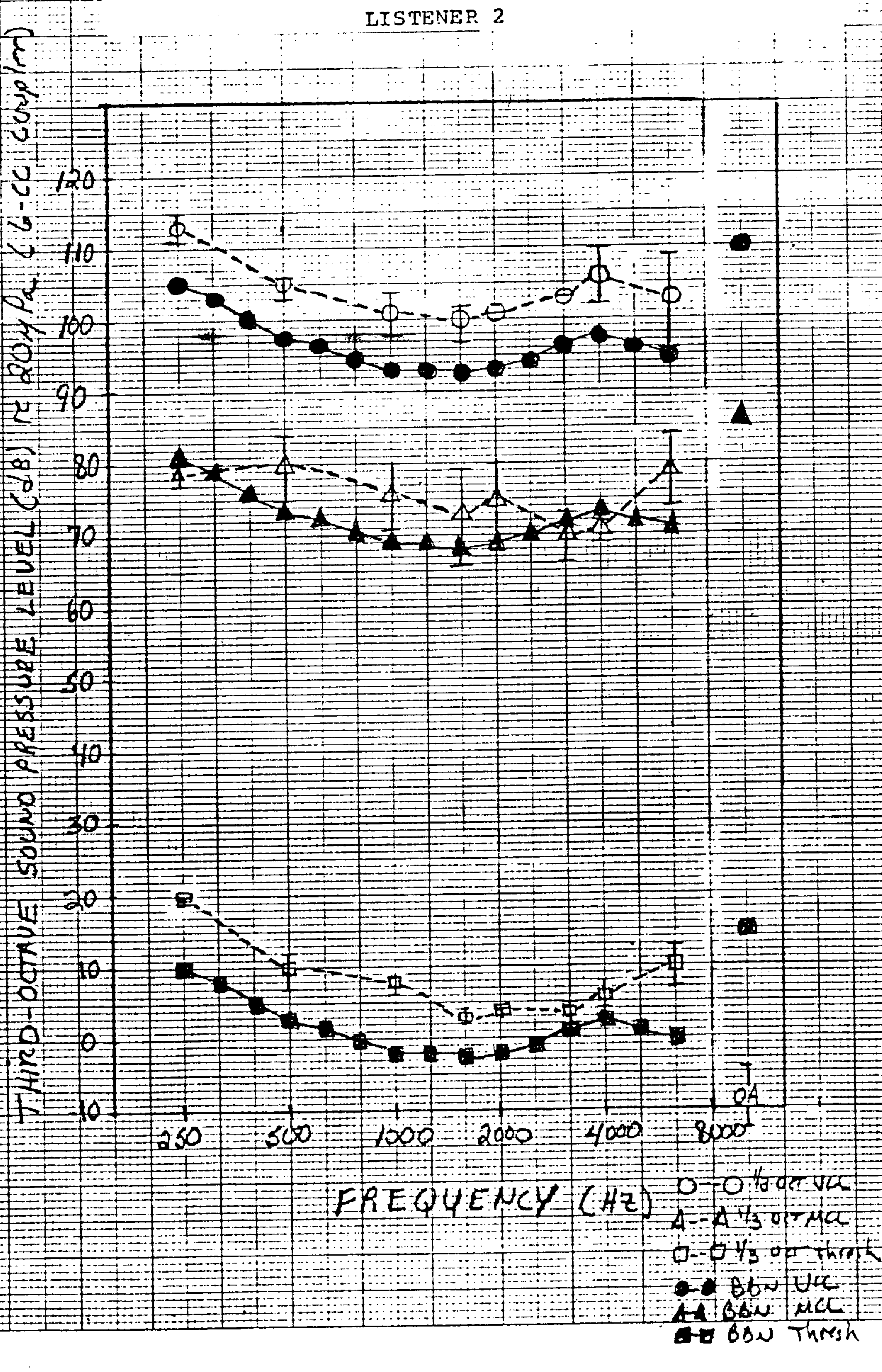

Figure 21. Third-octave bands of noise and threshold-shaped judgments of threshold, MCL and UCL for broad-band noise.

LISTENER 3

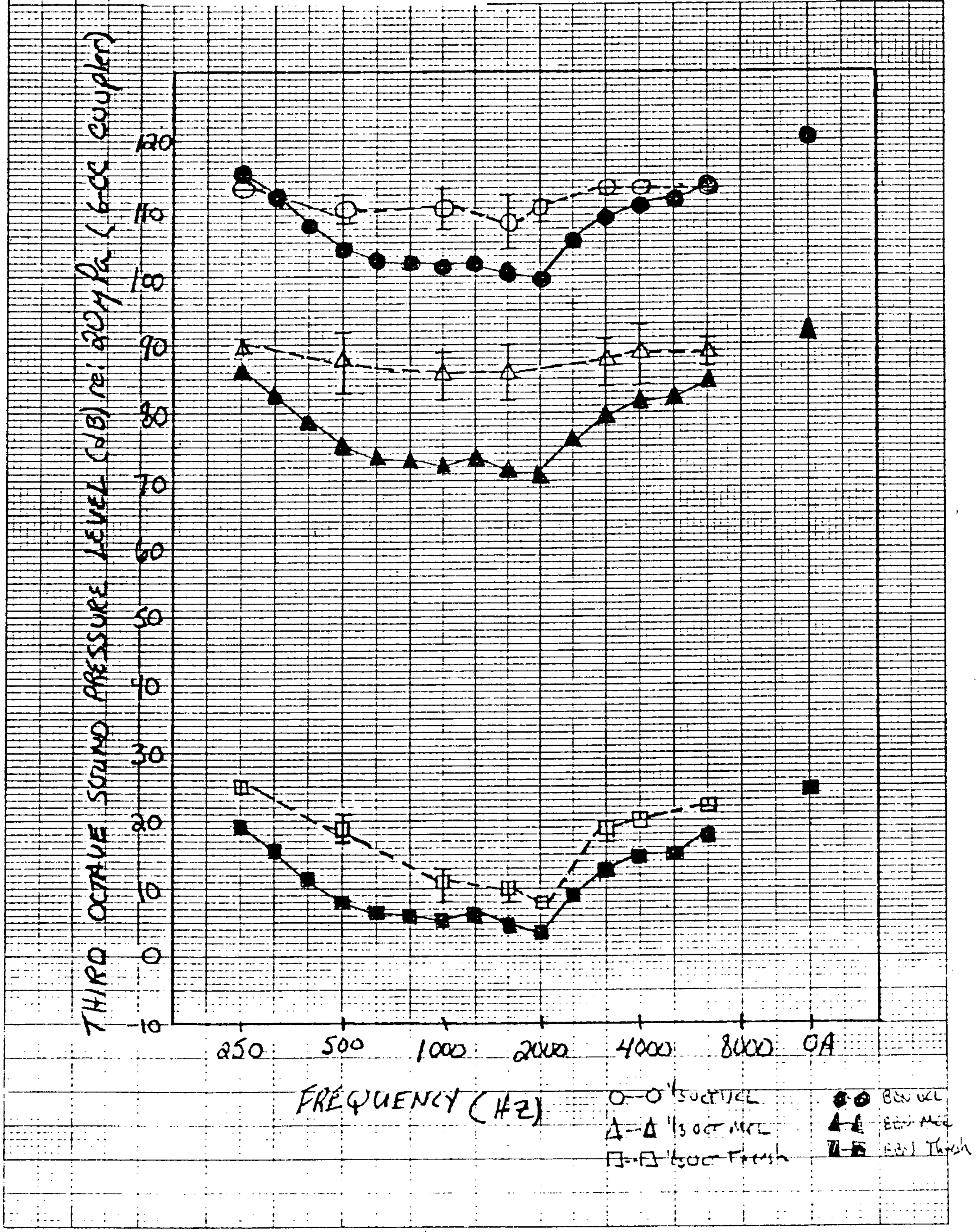

Figure 22. Third-octave bands of noise and MCL-shaped judgments of threshold, MCL and UCL for broad-band noise.

LISTENER 3

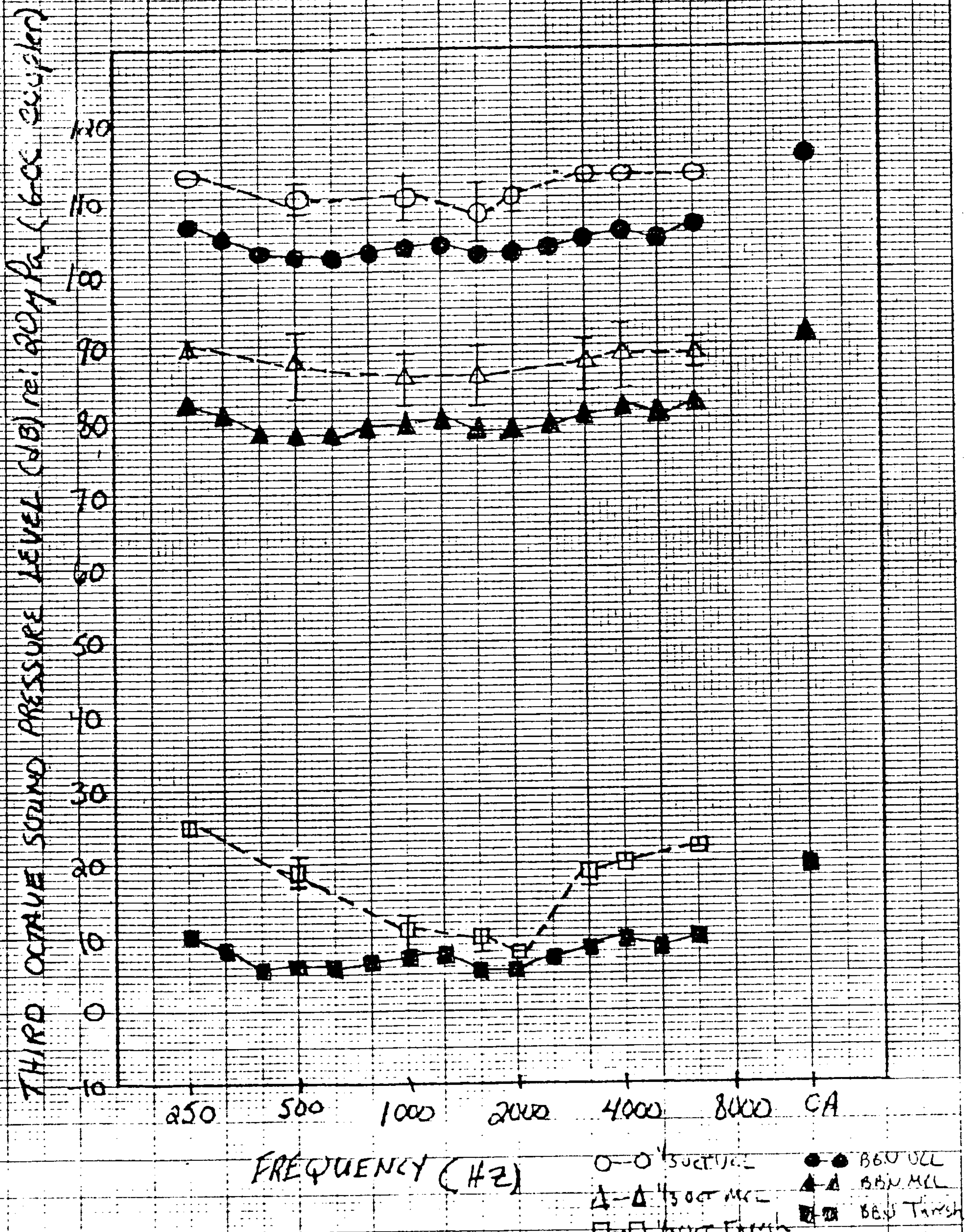

Figure 23. Third-octave bands of noise and UCL-shaped judgments of threshold, MCL and UCL for broad-band noise.

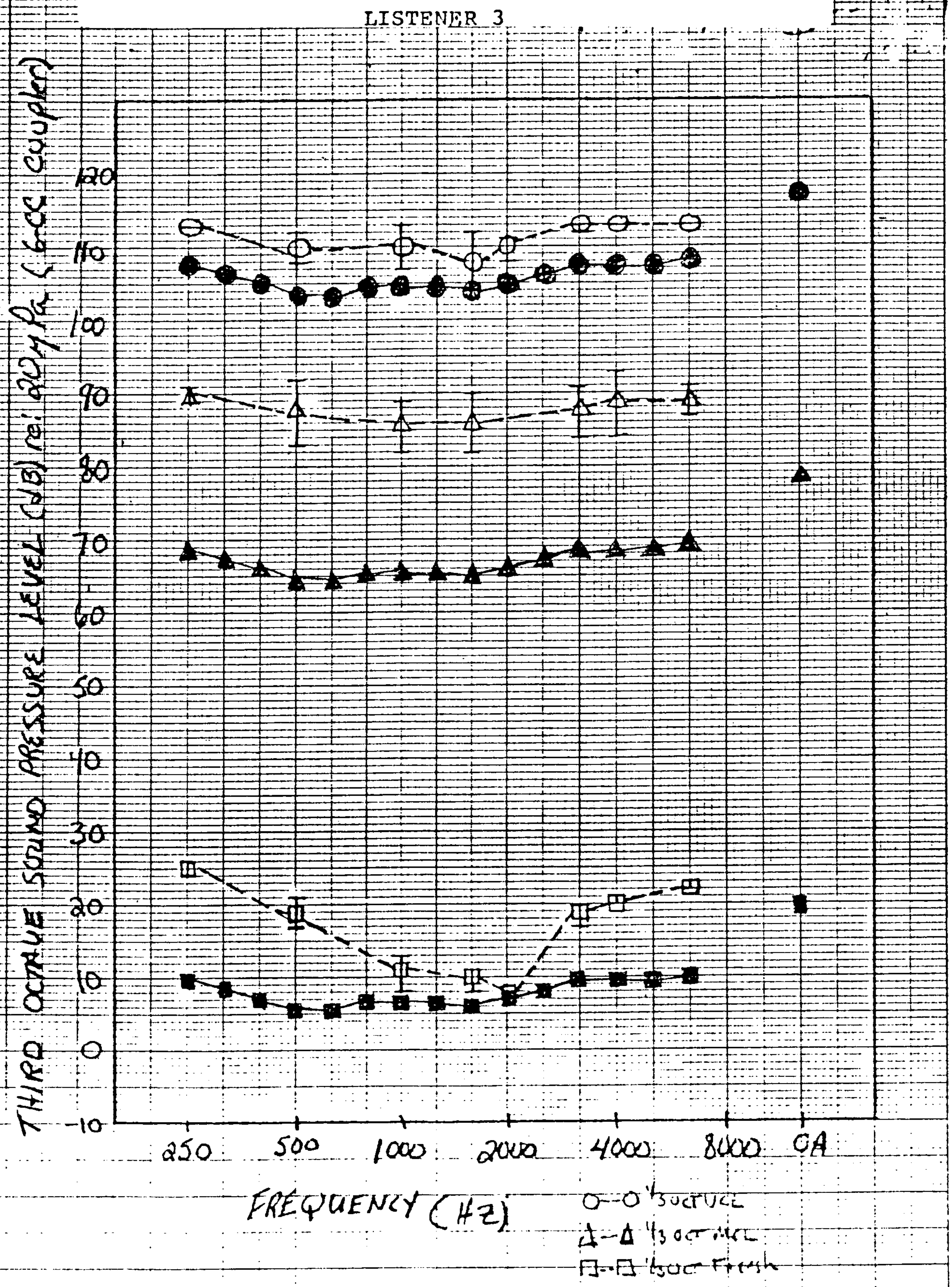

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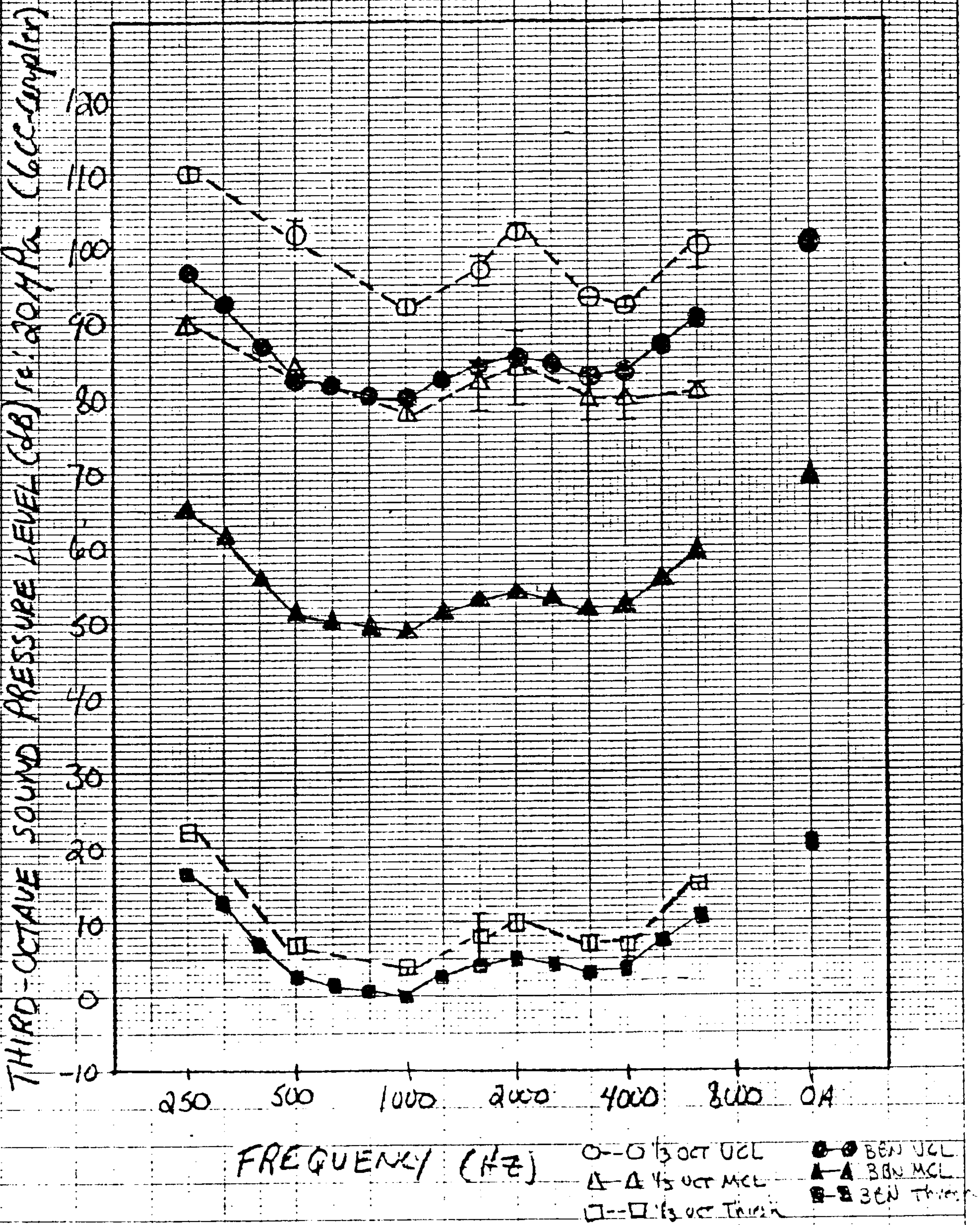
Figure 24. Third-octave bands of noise and thrshold-shaped judgments of threshold, MCL and UCL for broad-band noise.

LISTENER 4



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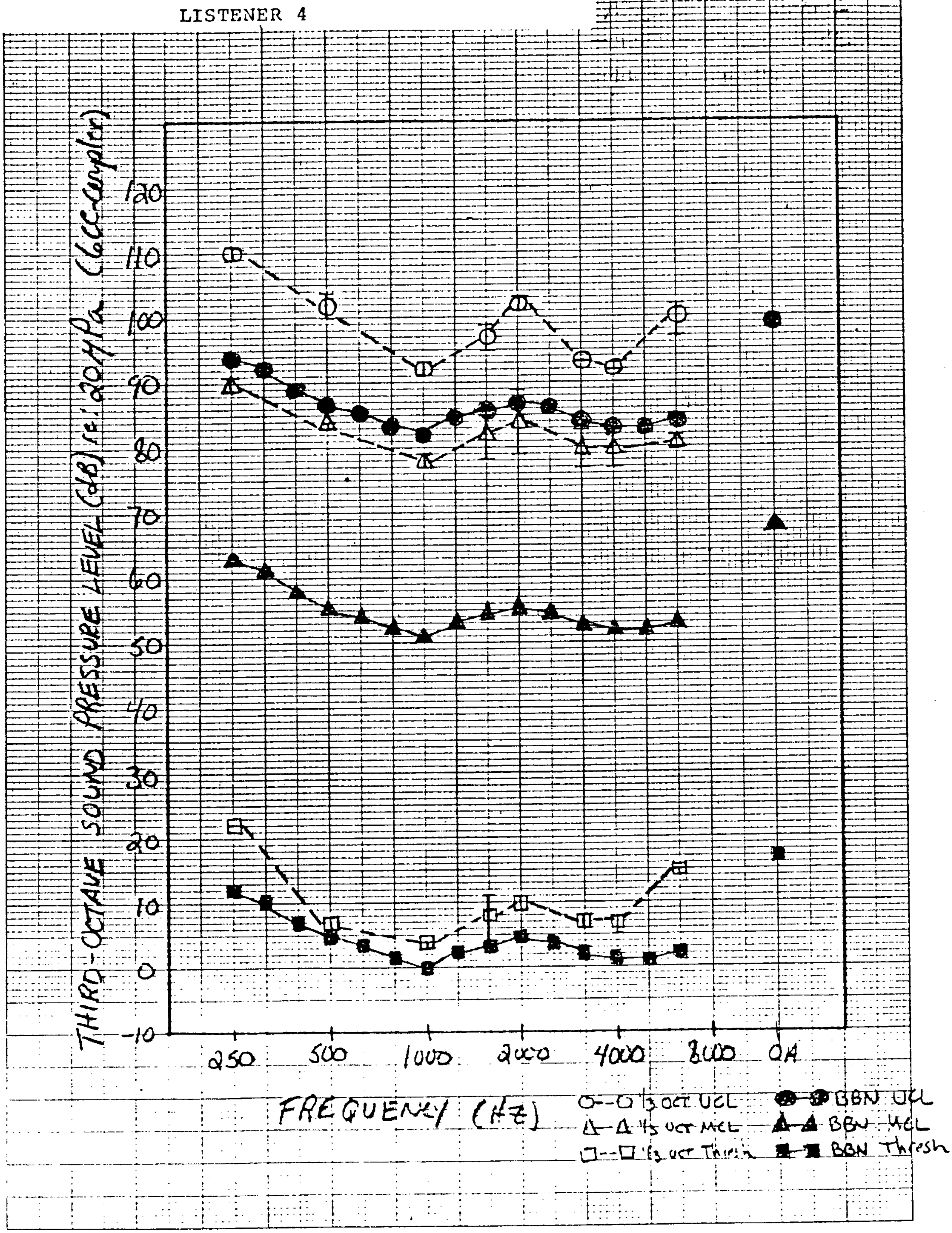
K+E 10 X 10 TO ½ INCH 7 X 10 INCHES KEUFFEL & ESSER CO. MADE IN U.S.A.

Figure 25. Third-octave bands of noise and MCL-shaped judgments of threshold, MCL and UCL for broad-band noise.



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K+E 10 X 10 TO 1/2 INCH 7 X 10 INCHES KEUFFEL & ESSER CO. MADE IN U.S.A.

Figure 26. Third-octave bands of noise and UCL-shaped judgments for threshold, MCL and UCL for broad-band noise.

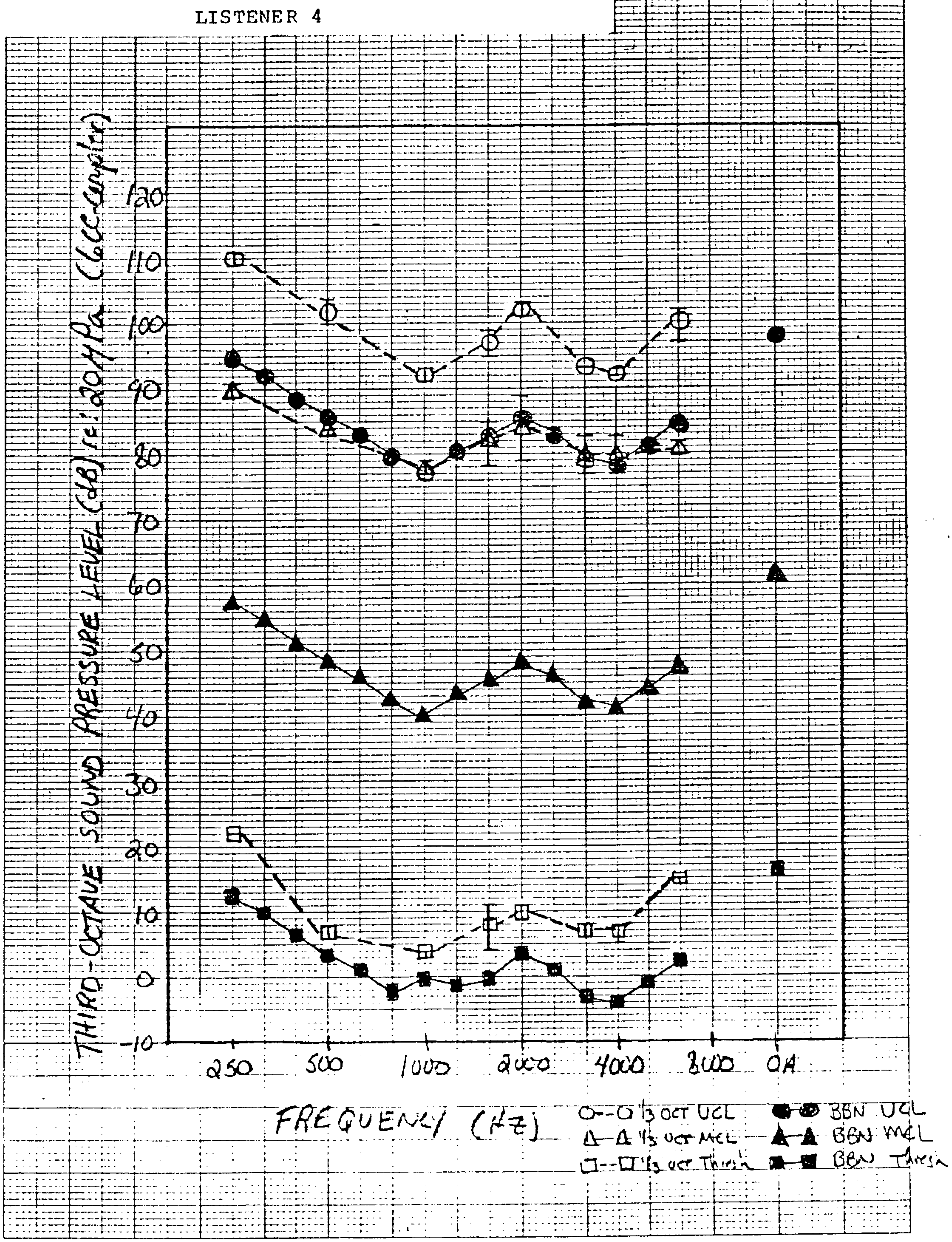


Figure 27. Third-octave bands of noise and threshold-shaped judgments of threshold, MCL and UCL for broad-band noise.

LISTENER 5

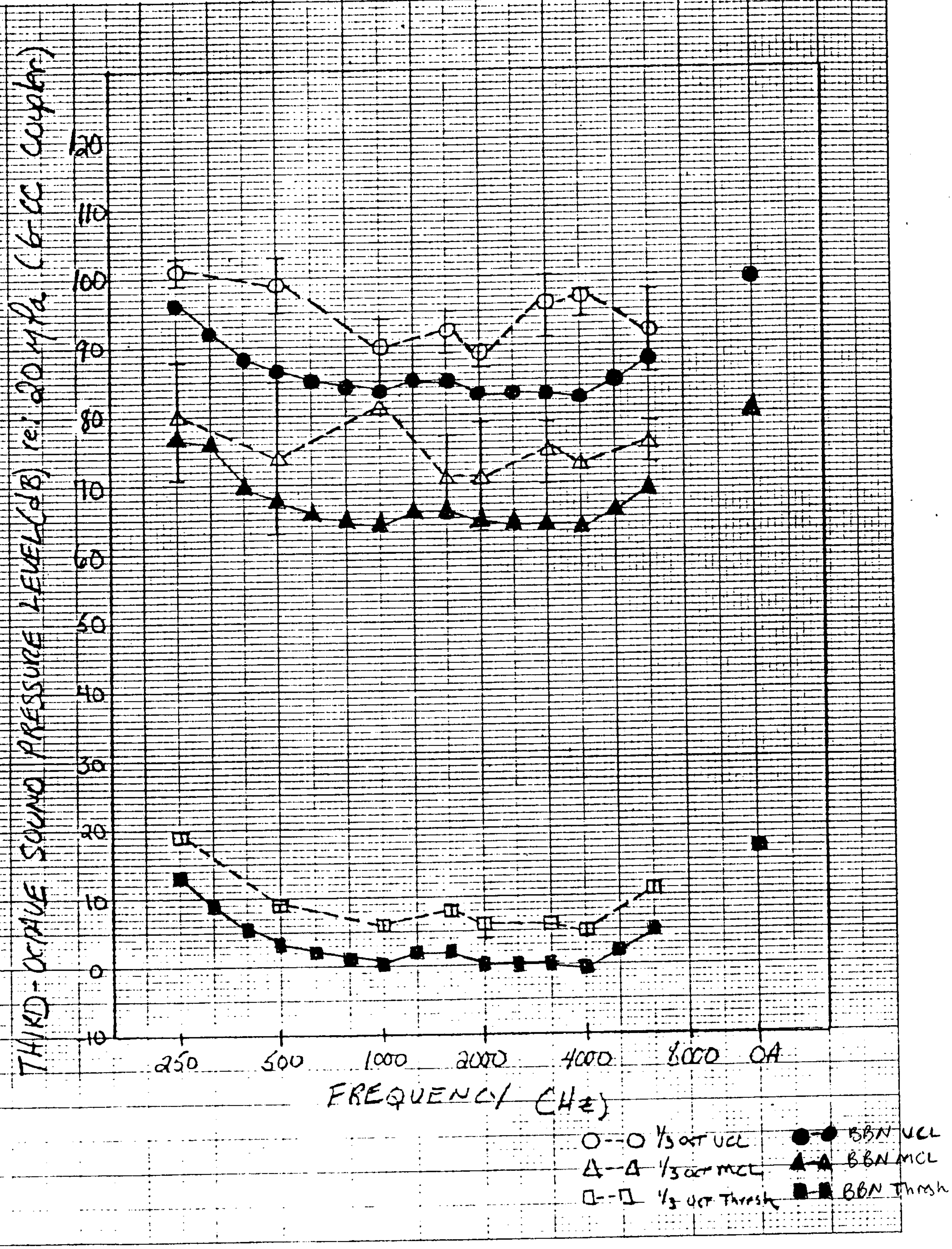
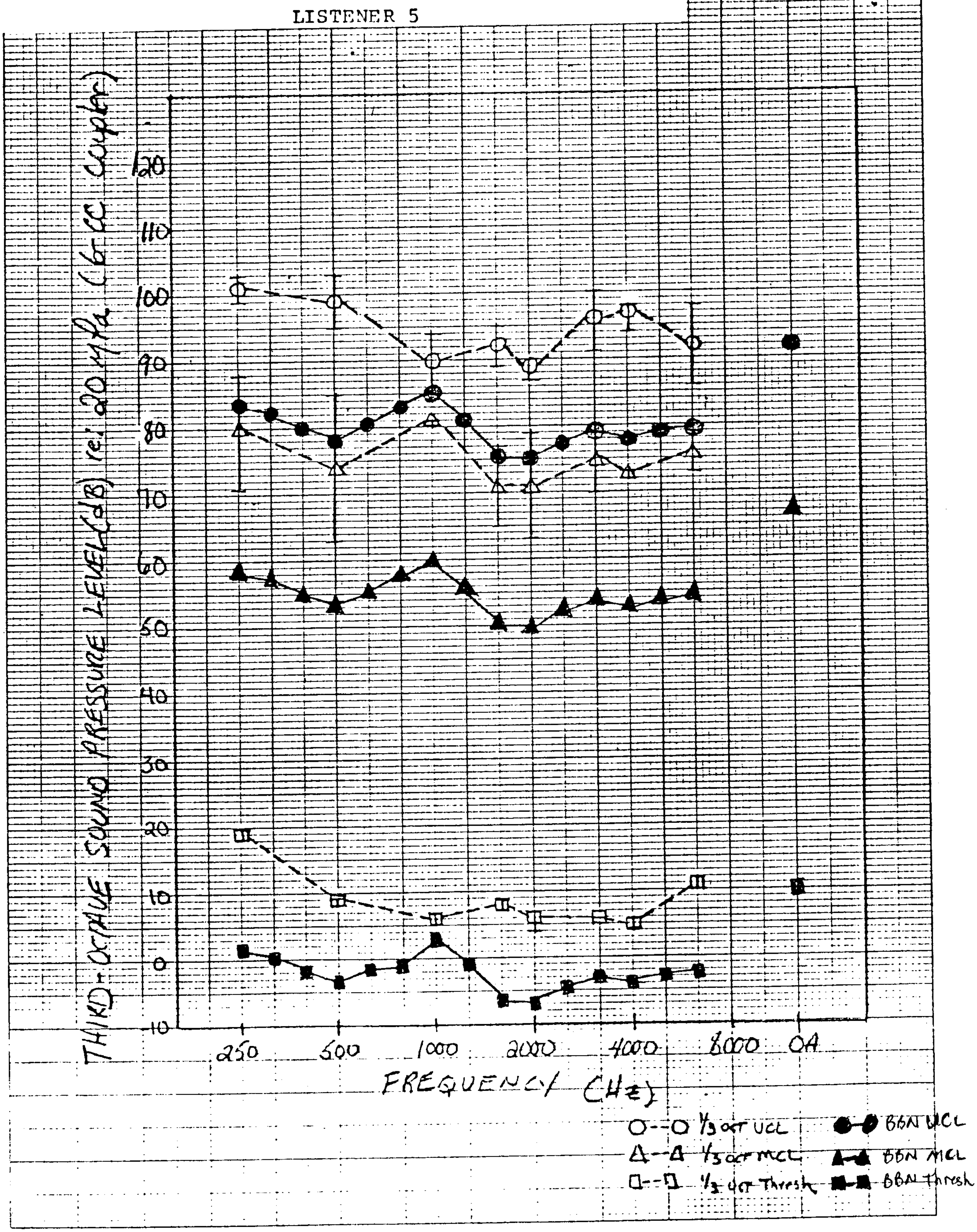


Figure 28. Third-octave bands of noise and MCL-shaped judgments for threshold, MCL and UCL for broad-band noise.



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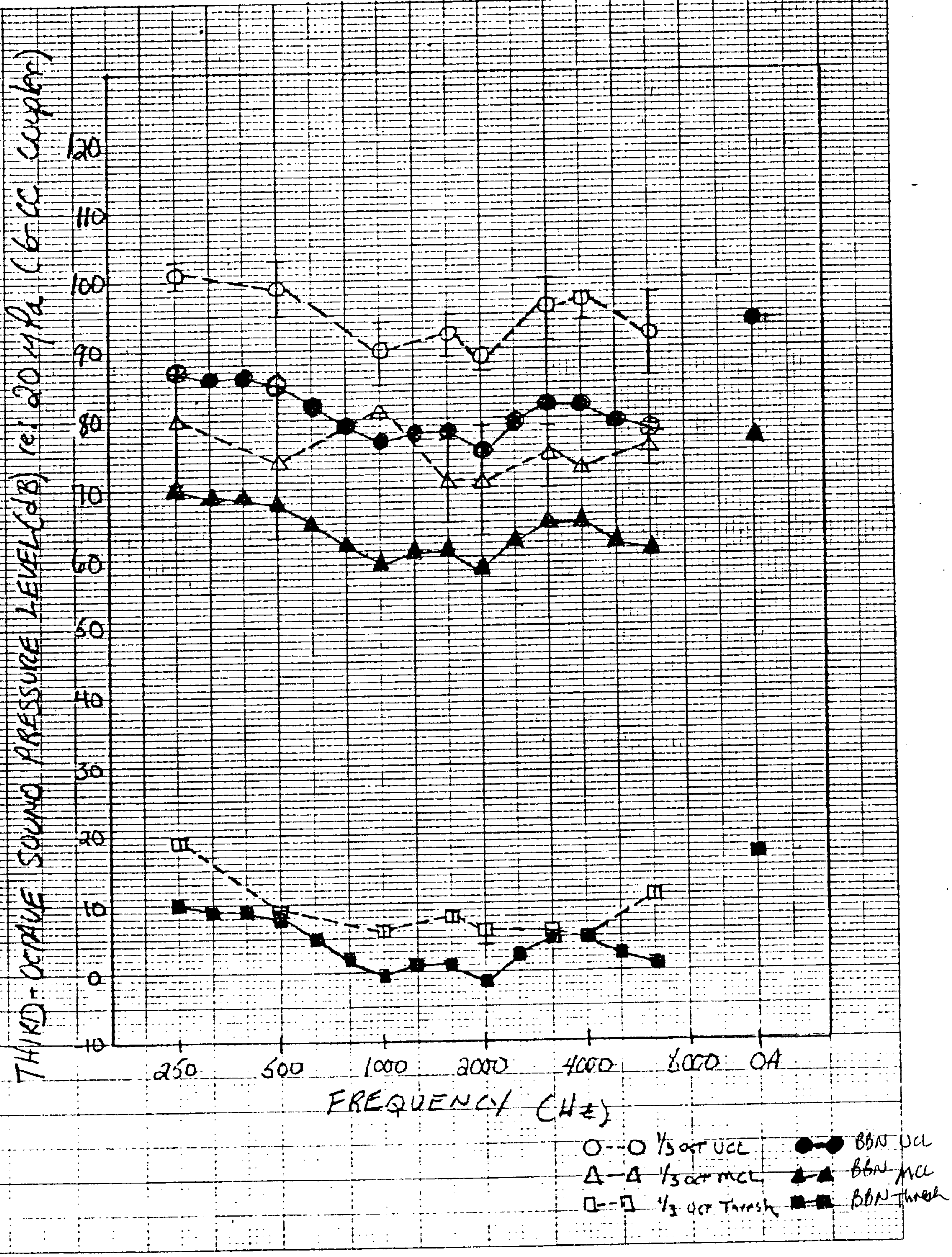
K•E 10 X 10 TO ½ INCH 7 X 10 INCHES KEUFFEL & ESSER CO. MADE IN U.S.A.

Figure 29, Third-octave bands of noise and UCL-shaped judgments of threshold, MCL and UCL for broad-band noise.

LISTENER 5



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K·E 10 X 10 TO ½ INCH 7 X 10 INCHES KEUFFEL & ESSER CO. MADE IN U.S.A.

Figure 30. Third-octave bands of noise and threshold-shaped judgments of threshold, MCL and UCL for broad-band noise.

LISTENER 6

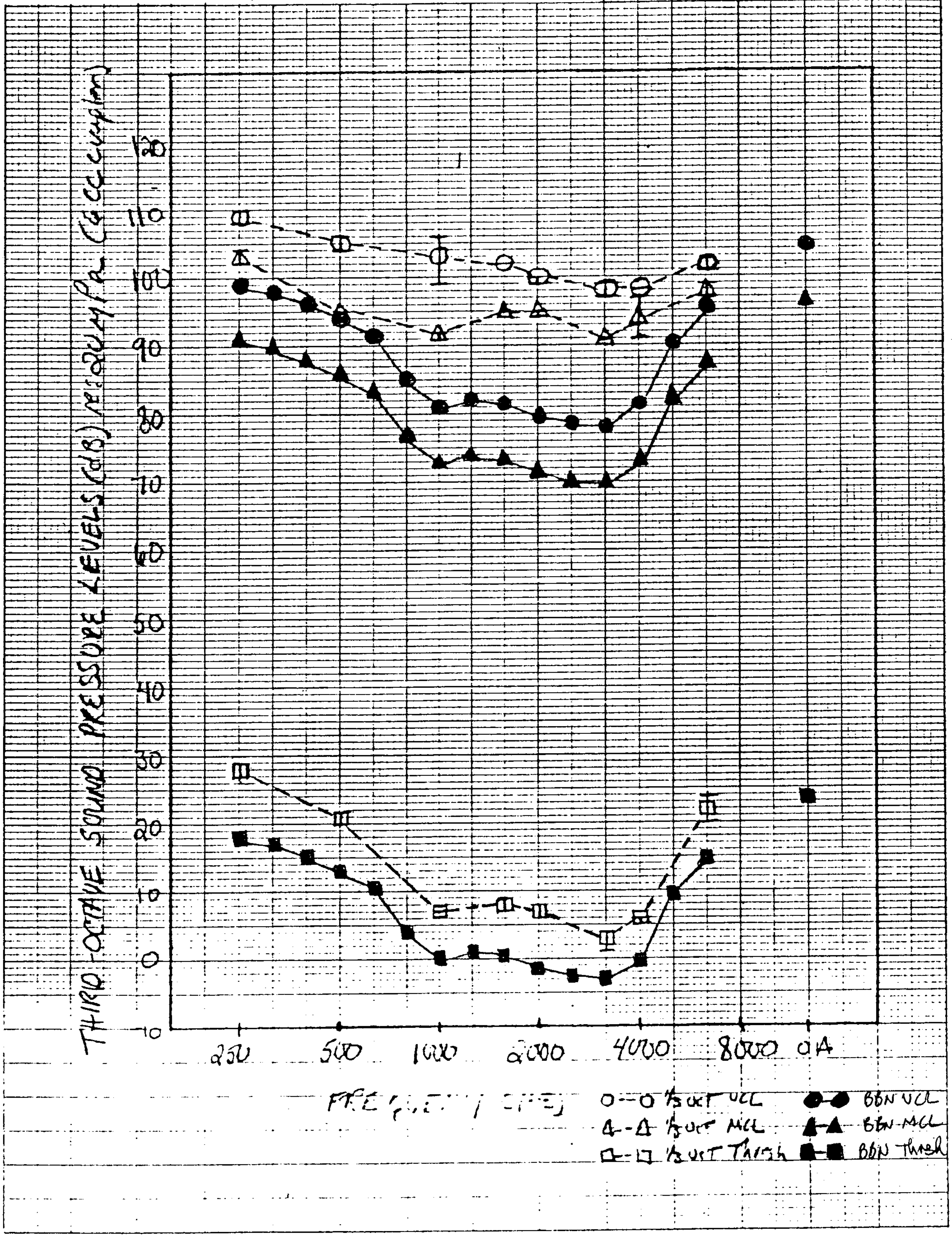
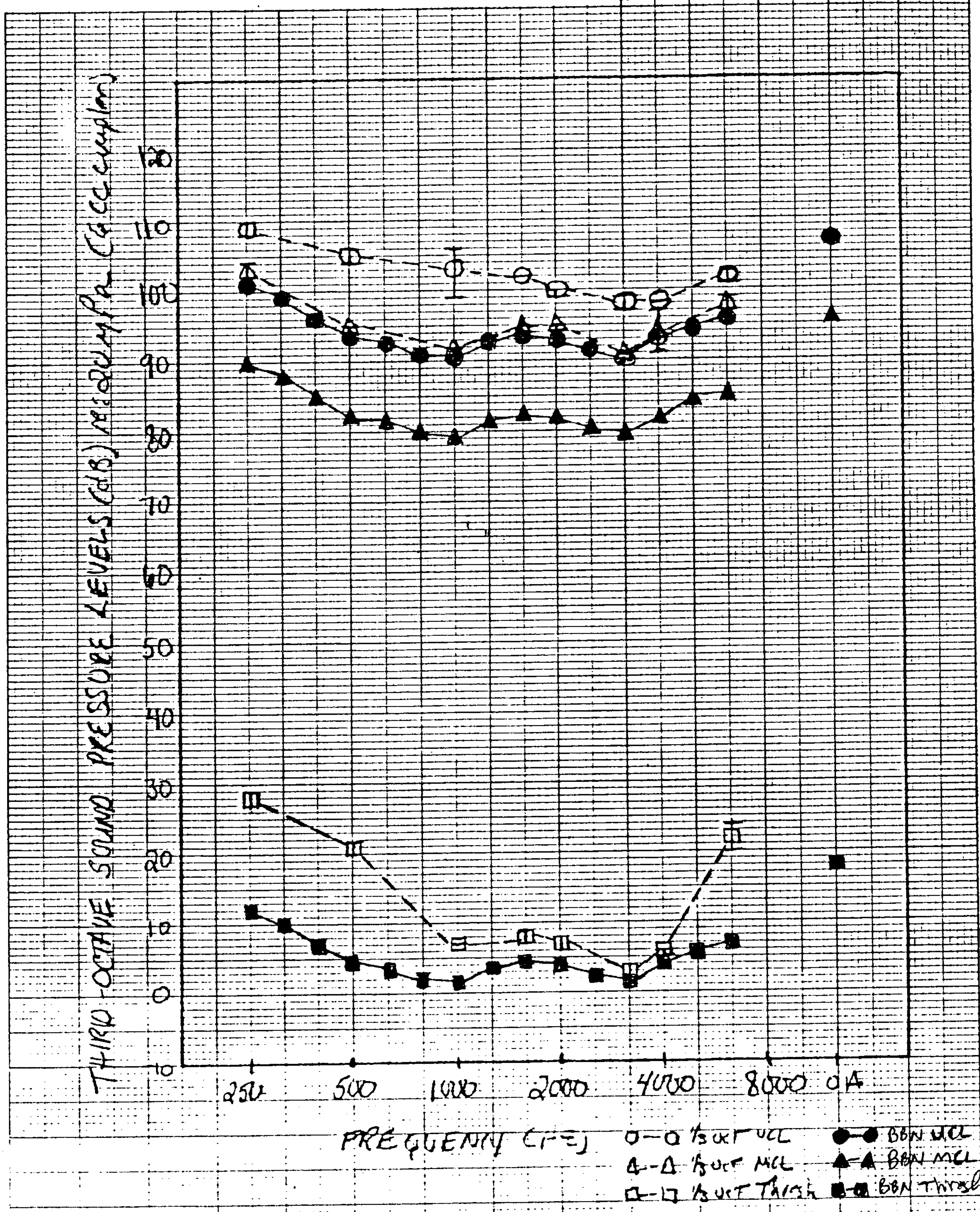


Figure 31. Third-octave bands of noise and MCL-shaped judgments of threshold, MCL and UCL for broad-band noise.

LISTENER 6



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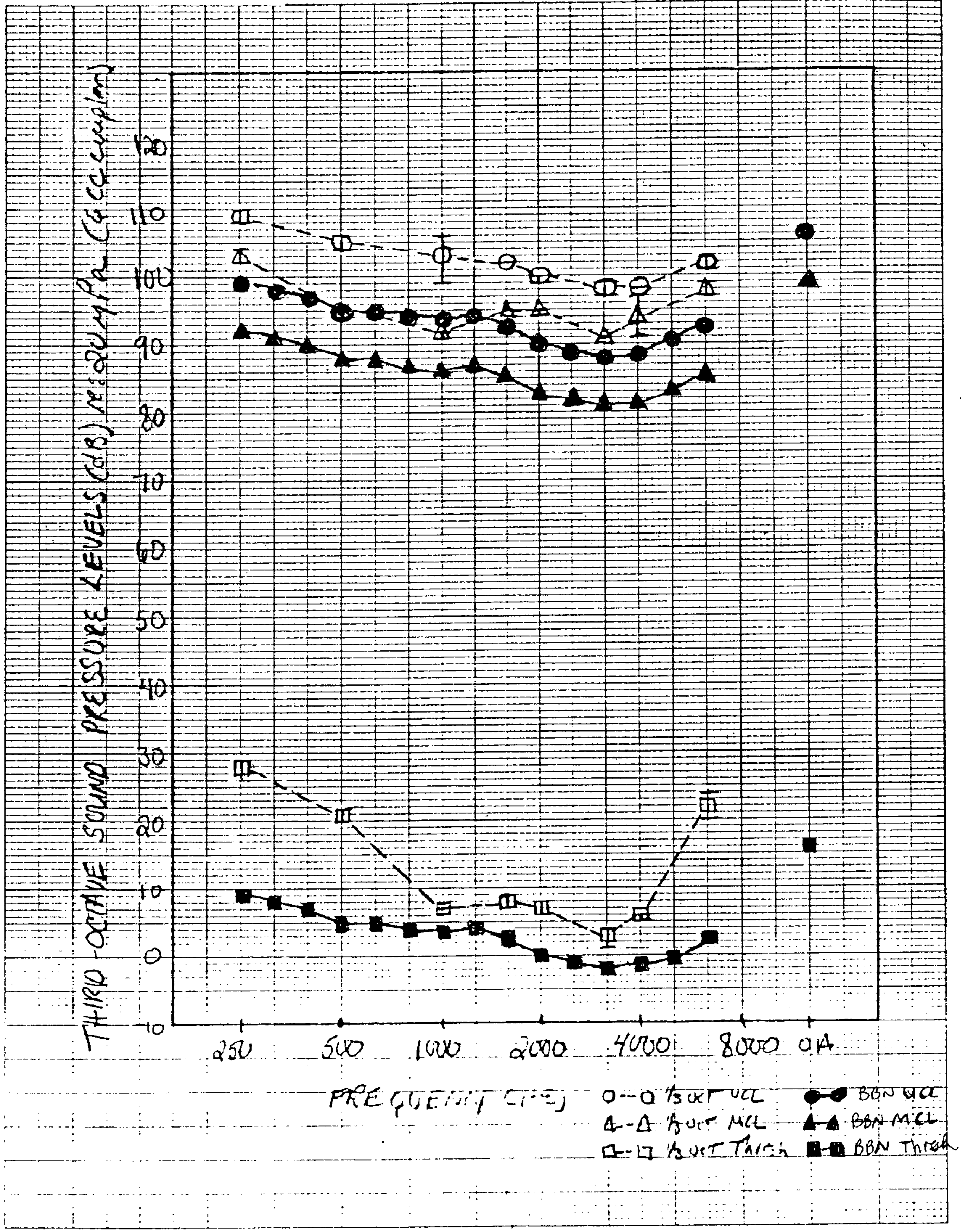
K-E 10 X 10 TO 1/2 INCH 7 X 10 INCHES KEUFFEL & ESSER CO. MADE IN U.S.A.

Figure 32. Third-octave bands of noise and UCL-shaped judgments of threshold, MCL and UCL for broad-band noise.

LISTENER 6



Loudness Summation. Comparisons of the third-octave band judgments and the broad-band measurements for threshold, MCL and UCL were made to determine the presence of summation. The following observations are seen when these comparisons are made;

Threshold: Measurements for the threshold-shaped broad-band noise contour are all within 10dB of the one-third octave threshold judgments across all six listeners. Slight loudness summation is present for all six listeners for the threshold-shaping. All listeners except listener 5 also show slight summation at threshold for the MCL and UCL-shaped broad-band stimulus. Listener 5 shows no summation at threshold for the UCL-shaped contour and an increase in summation at threshold for the MCL-shaped contour.

MCL: Listeners 1, 4, and 5 show significant summation at MCL for the MCL-shaped broad-band noise. As much as a 20dB SPL difference is noticeable at certain frequencies. Listeners 1 and 4 also display significant summation at MCL for the threshold-shaped and UCL-shaped broad-band stimuli, with listener 4 showing the largest amount of summation of all six listeners. For the UCL-shaped stimulus, listener 4 showed as much as 30dB SPL summation at MCL. Listeners 3 and 6 also show noticeable summation for the MCL-shaped broad-band noise, but to a lesser degree than other listeners. Listener 3 showed significant summation at MCL for the UCL-shaped stimulus. Only one listener failed to show any loudness summation (listener 2) and only showed summation at MCL for the threshold-shaped stimulus.

UCL: The largest loudness summation at UCL was shown by listeners

4, 5 and 6. Loudness summation at UCL for these listeners is especially significant because the level of uncomfort for these listeners for the broad-band noise now falls at the same level (SPL) as the MCL judgments for the one-third octave bands of noise. This means that the sound pressure level of the broad-band noise judged uncomfortably loud is the same as the sound pressure level judged comfortably loud for the one-third octave bands of noise. Listeners 1, 2 and 3 all show summation to a moderate degree at UCL for all three broad-band noise shapings.

To summarize, the most significant summation occured at MCL for all listeners (except listener 2 with no summation). Listeners 1, 4 and 5 show greatest summation at MCL and listeners 3 and 6 show moderate summation. All listeners show summation at UCL, but listeners 4, 5 and 6 have more important implications as their UCL's for broad-band noise are super-imposed on the MCL judgments for the one-third octave bands of noise. Last, little summation occurs at threshold across listeners.

DISCUSSION

Comparison with Other Studies.

Variability of judgments. The same judgments, stimuli and psychophysical procedure were used for a companion study with hearing-impaired listeners (Matsumoto, 1983). The standard deviation of a single measurement across frequencies (third-octave bands of noise) and listeners in that study are close to those of the present study at threshold (standard deviation: companion study, 3.2dB; present study, 2.4dB), MCL (companion study, 5.9dB; present study, 6.0dB) and UCL (companion study, 5.4dB; present study, 4.7dB) (Matsumoto, 1983). In a similiar study in which the threshold, MCL and UCL of hearing-impaired listeners were obtained with pulsed, third-octave bands of noise, the standard deviation of a single measurement at threshold (2.7dB) and UCL (4.3dB) was very close to the results of the above two studies (Skinner and Miller, 1983). The standard deviation at MCL, however, was substantially lower (4.1dB).

Loudness summation. It is clearly evident that loudness summation did occur in listeners 1, 3, 4, 5 and 6, and to a lesser degree for listener 2. For the five listeners in which substantial summation did occur, summation at MCL was largest (as much as 20-30dB), summation at UCL was less (6-15dB), and summation at threshold was even less (4.5-7dB). The large summation at MCL and somewhat less summation at UCL is in agreement with the results of the classic study by Scharf, Flottorp, and Stevens (1957) with normal-hearing listeners. The presence of some summation at threshold found in the present study does not agree with the results of Scharf (1959), who found that loudness decreases slightly at threshold for stimuli with a bandwidth larger than a critical band. The difference between these two sets of results may be related to the different stimuli and psychophysical procedures used.

Relation of Present Results to Hearing Aid Fitting.

Prior studies indicate that people with conductive hearing losses and some with mild-to-moderate cochlear hearing losses have normal loudness summation (Scharf and Hellman, 1966; deBoer and Boumeister, 1974; Martin, 1974; Bonding *et al*, 1978; Bonding, 1979). If a person with normal loudness summation is fitted with a hearing aid set to amplify sound and conversational speech to his MCL contour for third-octave bands of noise, he will reduce the overall gain to make the broad-band speech comfortably loud.

The question is "How much summation will a hearing-impaired listener, who has normal loudness summation capabilities, experience in everyday life?" Will it be 20-30dB at MCL, as it was for the normal-hearing listeners in this study, or will it be less. It can be argued that the broad-band noise (250-6300Hz) and a constant sound pressure level created a condition that occurs very infrequently in everyday life. The broad-band stimuli (including speech) that do occur are intermittent, vary in bandwidth and vary in the relative levels of sound in specific frequency regions. Loudness summation is less for these stimuli than for the broad-band noise used in the present experiment. Therefore, it is unlikely that listener's will be subjected to a noise containing the parameters of this experiment in their enviroment, except in noisy restaurants or large crowds. For these reasons, the overall gain of a hearing aid may be set too high according to the procedures mentioned above, but will not be 20-30dB too high.

As mentioned in the introduction, the MPO cannot be adjusted by the wearer, so it is critical that it be set appropriately. If the MPO is set on the basis of UCL judgments for third-octave bands of noise, then the listeners with normal loudness summation may have a hearing aid with the MPO set too high. The reason for this is that the broad-band noise UCL falls at a lower sound pressure level than that of the third-octave band UCL, meaning a listener's UCL for broad-band noise is lower than the MPO for the hearing aid. The data collected here for all six listeners supports this hypothesis. One distinct observation that can be made to further support this study can be found with the broad-band noise UCL's for listeners 4, 5 and 6. With summation occurring, the broad-band UCL now falls at or near the MCL judgments for the one-third octave bands of noise. This means that the level chosen as comfortable for the third-octave bands of noise is already considered uncomfortable for a broad-band stimuli. It will be possible then that by setting the gain of a hearing aid by using MCL judgments of one-third octave bands, we are automatically causing some listeners to reach their UCL when a broad-band stimulus is amplified.

Suggestions for Further Research.

The results of this study and the companion study with hearing-impaired listeners (Matsumoto, 1983) strongly suggest that we need to include loudness summation in our criteria for setting the overall gain and MPO of hearing aids for listeners with mild to moderately severe, sensorineural hearing losses. The question remains as to what degree of loudness summation should be expected. We need to explore further the effects of intermittancy, sharpness (von Bismark, 1974), and roughness (Plomp and Levelt, 1965; Fastl, 1977) on the loudness summation of broad-band sounds at MCL and UCL for both normal and hearing-impaired listeners.

SUMMARY

The occurrance of loudness summation in normal-hearing listeners is large at MCL and present, though to a lesser degree, at threshold and UCL. This result is in general agreement with the classic studies on loudness summation. This study has it's greatest implications for the proper setting of hearing aid gain and MPO levels. If the same results are found in the companion study by Matsumoto (1983) with hearing-impaired listeners, a change in the hearing-aid fitting procedure may be necessary. By setting the gain and MPO levels to judgments made on one-third octave bands of noise for threshold, MCL and UCL, we could, according to this data, be amplifying speech and other broad-band stimuli to uncomfortable listening levels for the listener. We would then be defeating our purpose as hearing therapists.

APPENDIX

NOISE THRESHOLD

(SET YOUR DIAL TO 0)

YOU WILL BE LISTENING TO PULSED NOISE. THE DIAL IN FRONT OF YOU WILL ALLOW YOU TO MAKE PULSED NOISE LOUDER OR SOFTER. LISTEN AND FIND THE LEVEL AT WHICH YOU CAN JUST BARELY DETECT THE PRESENCE OF THE PULSED NOISE.

FIND THIS LEVEL BY TURNING THE DIAL UP (UNTIL YOU HEAR THE PULSED NOISE), AND DOWN (UNTIL YOU CANNOT HEAR THE PULSED NOISE.) MOVE IN LARGER AND THEN IN SMALLER AND SMALLER STEPS UNTIL YOU HAVE "NARROWED IN" ON THE LEVEL AT WHICH YOU CAN BARELY DETECT THE PRESENCE OF THE PULSED NOISE.

WHEN YOU HAVE FOUND THE "JUST DETECTABLE" LEVEL FOR THE PULSED NOISE, CALL OUT THE NUMBER ON YOUR DIAL AND THEN RETURN IT TO POSITION 0.

MOST COMFORTABLE LISTENING LEVEL FOR NOISE

(SET YOUR DIAL ON 30)

YOU WILL BE LISTENING TO PULSED NOISE. THE DIAL IN FRONT OF YOU WILL ALLOW YOU TO MAKE THE PULSED NOISE LOUDER OR SOFTER. LISTEN AND FIND THE LEVEL THAT WOULD BE MOST COMFORTABLE FOR YOU TO LISTEN TO FOR A LONG TIME. CHOOSE THIS LEVEL BY PRESUMING THAT YOU MUST LISTEN TO THE NOISE TO OBTAIN INFORMATION FROM IT. (FOR EXAMPLE, PRETEND YOU ARE A PILOT AND ARE LISTENING TO A RADIO BEACON SIGNAL OR TO A PERSON GIVING DIRECTIONS.)

FIND THIS LEVEL BY TURNING THE DIAL UP AND DOWN, MAKING THE PULSED NOISE LOUDER AND SOFTER. MOVE IN LARGER AND THEN IN SMALLER AND SMALLER STEPS UNTIL YOU HAVE "NARROWED IN" ON THE LEVEL YOU FEEL IS MOST COMFORTABLE TO LISTEN TO IN ORDER TO RECEIVE INFORMATION FROM IT.

WHEN YOU HAVE FOUND YOUR MOST COMFORTABLE LISTENING LEVEL FOR THE PULSED NOISE, CALL OUT THE NUMBER ON YOUR DIAL AND THEN RETURN IT TO POSITION 30.

UNCOMFORTABLE LISTENING LEVEL FOR NOISE

(SET YOUR DIAL ON 30)

YOU WILL BE LISTENING TO PULSED NOISE. THE DIAL IN FRONT OF YOU WILL ALLOW YOU TO MAKE THE PULSED NOISE LOUDER OR SOFTER. LISTEN AND FIND THE LEVEL AT WHICH THE NOISE BECOMES UNCOMFORTABLE AND ABOVE WHICH YOU WOULD NOT WANT TO LISTEN FOR A LONG TIME.

FIND THIS LEVEL BY TURNING THE DIAL UP AND DOWN, MAKING THE PULSED NOISE LOUDER OR SOFTER. MOVE IN LARGER AND THEN IN SMALLER AND SMALLER STEPS UNTIL YOU HAVE "NARROWED IN" ON THE LEVEL ABOVE WHICH YOU WOULD NOT WANT TO LISTEN.

WHEN YOU HAVE FOUND THE LEVEL AT WHICH THE PULSED NOISE BECOMES UNCOMFORTABLE FOR YOU TO LISTEN TO, CALL OUT THE NUMBER ON YOUR DIAL AND THEN RETURN IT TO POSITION 30.

REFERENCES

Berger, K.W., Hagberg, N.S., and Rane, R.L.: Prescription of Hearing Aids: a Rationale. Kent, Ohio, Herald Publishing House, 1977.

Bonding, P.: Critical Bands in Menière's Disease, Audiology 18: 197-207, 1979.

Byrne D., and Tonisson, W.: Selecting the gain of hearing aids for persons with sensorineural hearing impairments. Scandanavian Audiology 5:51-59, 1976.

deBoer, E., and Bouwmeister, J.: Critical bands and sensorineural hearing loss. Audiology 13:236-259, 1974.

Fastl, Hugo: Roughness and temporal masking patterns of sinusoidally amplitude modulated broad-band noise. Psychophysics and Physiology Evans, E. and Wilson, J., eds., London; Academic Press, 1977, 403-414.

Martin, M.C.: Critical bands in sensorineural hearing loss. Scandanavian Audiology 3:133-140, 1974.

Matsumoto, J.: A study of threshold and loudness summation in listeners with sensorineural hearing impairments. Unpublished study, 1983.

Pascoe, D.: An approach to hearing aid selection. Hearing Instruments, 29:12, 1978.

Pascoe, D.: Clinical implications of nonverbal methods of hearing aid selection and fitting. Seminars in Speech, Language and Hearing Vol. 1, No. 3; August 1980.

Plomp, R. and Levelt, W.: Tonal consonance and critical bandwidth Journal of the Acoustical Society of America (JASA) 38:548-560.

Scharf, B.: Critical bands and the loudness of complex sounds near threshold. J. Acoust. Soc. Am.(JASA) 31:365-370, 1959.

Scharf, B. and Hellman, R.: Model of loudness summation. J. Acoust. Soc. Am.(JASA) 40:71-78, 1966.

von Bismark, G.: Sharpness as an attribute of the timbre of steady sounds. Acustica 30:159-172, 1965.

Zwicker, E., Flottorp, G. and Stevens, S.S.: Critical bandwidth in loudness summation. J. Acoustic. Soc. Am.(JASA) 29:548-557, 1957.

ADDITIONAL REFERENCES

Bonding, P. et al: Estimation of the critical bandwidth from loudness summation data. Scand. Audiology 7:91-97, 1978.

Skinner, M.W.: Speech-intelligibility in noise-induced hearing loss: effects of high-frequency compensation. J. Acoust. Soc. Am. 67:306-317, 1980.

Skinner, M.W. and Miller, J.D.: Amplification bandwidth and intelligibility of speech in quiet and noise for listeners with sensorineural hearing loss. Audiology 22:253-279, 1983.